NREL/TP-425-8195 • UC Category: 1500 • DE95013145

Development of a Dedicated Ethanol Ultra-Low Emission Vehicle ULEV—Phase 2 Report

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A national laboratory of the U.S. Department of Energy
Managed by the Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. DE-AC36-83CH10093

Prepared under Subcontract Number YAW-3-12243-01

September 1995

2951

Preface

This work was conducted by Southwest Research Institute (SwRI), San Antonio, Texas, under Subcontract No. YAW-3-12243-01, SwRI project number 03-5901 for the U.S. Department of Energy (DOE) in Washington, D.C., and the National Renewable Energy Laboratory (NREL) in Golden, Colorado. The contributions of technical monitors Christopher P. Colucci and Brent K. Bailey of NREL, John A. Russell and John Garbak of DOE, and subcontract administrators Ernest G. Oster and Brian Rieper of NREL are gratefully acknowledged. The expertise of Ms. Jo Ann Brown in preparing this report is also greatly appreciated.

The objective of this 3.5-year project is to develop a commercially competitive vehicle powered by ethanol (or an ethanol blend) that can meet California's ultra-low emission vehicle (ULEV) standards and equivalent corporate average fuel economy (CAFE) energy efficiency for a light-duty passenger car application. The definition of commercially competitive is independent of fuel cost, but does include technical requirements for competitive power, performance, refueling times, vehicle range, driveability, fuel handling safety, and overall emissions performance.

This report summarizes the second phase of this project, which lasted 12 months. This report documents two baseline vehicles, the engine modifications made to the original equipment manufacturer (OEM) engines, advanced aftertreatment testing, and various fuel tests to evaluate the flammability, lubricity, and material compatibility of the ethanol fuel blends.

Executive Summary

Ethanol is attractive as an alternative fuel for spark-ignition engines for a variety of reasons. First, it is a renewable fuel, derivable from biomaterials. Many alternative fuels are derived from petroleum, and their long-term potential is therefore limited by the availability of petroleum. Second, ethanol has an average octane number ((R+M)/2) of about 106, compared to about 87 for regular grades of gasoline. The higher octane number implies greater resistance to knock, which allows for higher compression ratios that produce greater cycle (and therefore fuel) efficiency. Third, because ethanol is derived from biofuels, there is arguably no net increase in greenhouse gases. This is in sharp contrast to petroleum-fueled vehicles, and especially natural gas-powered vehicles that typically have low nonmethane hydrocarbon emissions, but high emissions of methane, a significant greenhouse gas. Fourth, ethanol is nontoxic, unless toxins are added to prevent human consumption. Fifth, the fuel is naturally low in evaporative emissions, although in practice this potential advantage is offset with the addition of gasoline additives to increase the vapor pressure for starting and fuel tank safety. Sixth, the reactivity factor (potential for exhaust products to form ozone) for ethanol is significantly less than for gasoline, with preliminary estimates being about 0.68 (Marshall 1994) that of standard gasoline. Seventh, the principal emissions are unburned ethanol and acetaldehyde, formed in the first oxidation step of ethanol, which make a simpler mix of gases that must be treated in the exhaust catalyst than those produced by gasoline combustion.

Ethanol also presents engineering challenges that are present with any new fuel. For ethanol, low-temperature cold-starting and fuel tank flammability are problems. The energy content of ethanol is about 63% that of gasoline, which decreases range or increases fuel tank size. Current ethanol costs are high enough to make it noncompetitive with gasoline, although encouraging cost reductions are being obtained.

Southwest Research Institute has been contracted by DOE and NREL to develop a dedicated ethanol- or ethanol-blend-fueled ULEV. This vehicle must be competitive with conventional gasoline-powered vehicles in cost, reliability, and performance, but not in fuel cost.

Southwest Research Institute proposed to make changes in the engine and aftertreatment systems of a standard OEM production vehicle to increase its efficiency and simultaneously reduce its emissions to ULEV standards. The vehicle platform selected for these modifications was the 1993 Ford Taurus flexible fuel vehicle (FFV) designed to operate on M85 and gasoline, and equipped with the 3.0-liter Vulcan engine. Selecting a vehicle that had materials compatible with both methanol and gasoline resulted in no material compatibility problems with ethanol fuels. The Ford FFV was the only U.S.-made FFV readily available when the vehicles were purchased. Two vehicles were purchased so that simultaneous testing of the engine modifications and the advanced aftertreatment devices could be conducted.

Three major changes to the engine were described by Bourn et al. (1994), and all three have been completed in Phase 2. These include increasing the compression ratio of the engine from 9.3 to 11.0 to take advantage of the high octane number of ethanol blend fuels, changing the fuel injectors to fine-spray air-assist injectors, and using a SwRI rapid prototype engine control system engine controller (RPECS) to provide more precise air-fuel ratio control and to control the aftertreatment system.

Although several advanced aftertreatment devices will be evaluated during this project, only electrically heated catalysts (EHCs) were scheduled for preliminary evaluation during Phase 2. Although the baseline vehicle emissions were quite low, adding the EHC to the standard unmodified OEM vehicle further reduced exhaust emissions. All tests were conducted with a vehicle mileage of about 4,000 miles, with the catalysts aged as described in this report. Carbon monoxide was reduced about 53% from the baseline vehicle to

vehicle to 0.80 g/mi, about one-half the ULEV standard of 1.7 g/mi at 50,000 miles. Nitric oxide was reduced about 12% from the baseline vehicle to 0.068 g/mi, or less than one-half the ULEV standard of 0.2 g/mi at 50,000 miles. Nonmethane organic gases (NMOGs) estimated from hydrocarbons were reduced 49% from the baseline vehicle to about 0.052 g/mi, close to, but higher than the 0.040 g/mi NMOG standard. Catalyst aging factors are not available for this aftertreatment system, but emissions measured at 4,000 miles are presumably significantly less than the ULEV standards for 50,000 miles to account for catalyst degradation.

During Phase 3, the engine control system will be developed sufficiently to provide reliable low-temperature cold starts and produce very low engine-out emissions. Also during Phase 3, other advanced aftertreatment systems will be evaluated.

List of Abbreviations

Abbreviation	Description
AMA	Automobile Manufacturers Association
ASTM	American Society for Testing and Materials
BOCLE	Ball on Cylinder Lubrication Evaluator
CAFE	corporate average fuel economy
DOE	U.S. Department of Energy
DSP	digital signal processor
ECU	engine control unit
EHC	electrically heated catalyst
FID	flame ionization detector (for hydrocarbons)
FIDHC	hydrocarbons measured by flame ionization detector
FIDRCH 4	FID response factor for methane
FIDRETH	FID response factor for ethanol
FFV	flexible fuel vehicle
FTP	U.S. federal test procedure (light-duty, for emissions testing)
IMEP	indicated mean effective pressure
LEV	low-emission vehicle
LFE	laminar flow element
MAF	mass air flow
MBT	minimum timing advance for best torque
ms	milliseconds
NMHC	hydrocarbons excluding methane
NMOG	nonmethane organic gases
NREL	National Renewable Energy Laboratories
OEM	original equipment manufacturer
PEI	Petroleum Equipment Institute
PW	pulse width
RAF	reactivity factor
RPECS	rapid prototyping engine control system
RVP	Reid vapor pressure (at 100° F)
SMD	Sauter mean diameter
SwRI	Southwest Research Institute
TDC	top-dead-center
TESS	Trajectory and Evaporation of Spray Systems
TLEV	transitional low emission vehicle
ULEV	ultra-low emission vehicle
UNLG	unleaded gasoline
μm	micrometers

Overall Project

This report summarizes progress made toward developing an ethanol-fueled ULEV. The effort was divided into six tasks, and the progress is reported separately for each task. However, a few items were not specific to one task and are discussed in this section.

Vehicle Platform Choice

As discussed by Bourn et al. (1994), a 1993 Ford Taurus FFV was chosen for modification to meet ULEV standards. The logic for choosing this vehicle was as follows. First, a significant amount of work has gone into developing materials suitable for use with alcohol fuels. This is especially true for fuel tanks, fuel pumps, fuel lines, and fuel injectors, all of which are typically of different materials than for many standard gasoline-fueled vehicles. Instead of working to redevelop these materials, the decision was made to choose a vehicle designed to be operated on alcohol fuels. In the U.S., production vehicles designed to operate on alcohol are all designed as FFVs, or vehicles that operate on methanol/gasoline blends in the range from 85% methanol/15% gasoline to 100% gasoline. Recently some FFVs have been designed to run on ethanol rather than methanol.

Having chosen an FFV for the beginning platform, a particular manufacturer needed to be chosen. Because this work was funded by DOE, the vehicle had to be produced by a U.S.-based manufacturer. At the time the choice was made, GM had decided to stop producing FFVs, although there were many 3.1-liter Chevrolet Lumina vehicles in fleets. Chrysler was switching between vehicles and engines for its FFVs. Therefore, the Ford Taurus FFV with the 3.0-liter Vulcan engine was chosen as the starting platform. An advantage of this choice was that the vehicle had low emissions to start with, meeting transitional low-emission vehicle (TLEV) standards. A disadvantage was the relatively old engine design, a push-rod, two-valve per cylinder engine with a "bathtub" combustion chamber.

Because work was being conducted on the engine and the aftertreatment systems simultaneously, two 1993 Ford Taurus FFVs were obtained. The first was used in the standard production form but with various advanced aftertreatment systems. The second was used for engine development, and the engine was removed and placed in an engine test cell in a refrigerated chamber. Results from both these efforts shall be combined in one demonstrator vehicle.

Accelerated Schedule

At NREL's and DOE's request, SwRI submitted a proposal to accelerate the project from the originally proposed 42 months to 32 months. That proposal was approved after the end of Phase 2. That proposal included the development of a digital signal processor (DSP) based engine controller, the development and application of model-based controls with the help of consultant Robert Weeks, consulting by Mr. David Gardiner concerning low-temperature cold-start, and increased efforts in managing the overall project and incorporating technologies developed at NREL and other laboratories.

Technical Papers

Two technical papers were written and the accompanying presentations given concerning this project. A technical paper and presentation were prepared for the 1994 Annual Automotive Technology Development Contractors' Coordination Meeting in Detroit. A paper was also presented at the SAE Congress in February 1995. This second paper described estimates of fuel evaporation rates using the trajectory and evaporation of spray systems (TESS) code. The calculations included estimates for bench tests, where high-quality data for drop sizes and fuel vaporization rate were available for comparison with calculated results, and in-cylinder computations, where there is little knowledge about evaporation rates. The capability for in-cylinder calculations was developed on a previous NREL/DOE project, and the in-cylinder calculations were for the Ford 3.0-liter high-compression engine being developed for this project.

Table of Contents

Table of Contents (Cont'd)

List of Figures

List of Tables

Task 1 Fuel Blending and Testing

Objective

The objective of Task 1 was to determine the effects of ethanol fuel-additives on fuel tank flammability, cold startability, corrosion, wear, and lubricity.

Introduction

Fuel tank flammability is a safety concern that has been sometimes overlooked because very few (if any) fire-related accidents in automobiles have been attributed to explosions within the fuel tank. Most accidents involving fire are caused by fuel tank rupture. Spilled gasoline is the worst of fire hazards because its vapors quickly envelop the vehicle causing a tumultuous deflagration. Other fire hazards involve fuel leaks in the engine compartment where the hot exhaust manifold and corona discharge around ignition wires are potential ignition sources.

At temperatures above -10°C (14°F), the concentration of gasoline fumes in the vapor space of an automotive fuel tank is above the rich flammability limit (Goodger 1980). When the fuel temperature is below ≈-40°C (≈-40°F) the vapor concentration falls below the lean flammability limit. Between -10°C (14°F) and -40°C (-40°F), the vapors are flammable and could be ignited if subjected to a sufficiently strong ignition source. Temperatures that define the flammable range of the fuel vapor are termed the upper and lower temperature limits of flammability. Temperature limits of flammability are affected by Reid vapor pressure (RVP) and fuel composition.

A primary objective in Task 1 was to develop correlations of vapor pressure with temperature that could be used to predict temperature limits of flammability and cold startability. Cold start depends on the rate at which fuel can evaporate at low temperatures. Vapor phase equilibrium plays an important role in the evaporation of fuel droplets. The results of Task 1 will give important information for evaporation models used to predict cold start in ethanol fueled engines.

Combustion associated corrosion and wear were discussed in Phase 1 (Bourn et al. 1994). Fuel lubricity, which is important to fuel pump and fuel injector wear, is a topic of the present report. It is measured in terms of a wear pattern produced as the result of rubbing two metal surfaces together in the presence of the fuel. Experience has shown that oxygenated fuels have lubricating properties similar to gasolines. However, alcohols absorb water, which degrades fuel lubricity.

In Task 1, measurements of vapor pressure, temperature limits of flammability, and fuel lubricity were made on E100 (neat ethanol), Ed85 (85% denatured ethanol, 15% gasoline), and various blends of neat ethanol and blending stocks. The effects of water absorption and dissolved oxygen on fuel lubricity are addressed.

Test Fuels

The fuels included E100, gasoline, a baseline fuel Ed85, six blends of neat ethanol that contained 15% unleaded gasoline, butane, pentane, isopentane, C_5/C_6 isomerate, and diethyl ether. In addition, six similar blends that contained 5% of the same additives were made. The baseline fuel Ed85 is also referred to as E80 because the denatured ethanol is often 5% gasoline. Hence, the terms Ed85 and E80 are interchangeable in this report.

Octane Number Tests

An outside lab determined octane numbers on the Ed85 (or E80) fuel with the results shown in Table 1-1. These results suggest a blending octane number (R+M)/2 for the neat ethanol was 105.7. That is, the gasoline lowers the (R+M)/2 octane number of neat ethanol from about 105.7 to 102.1, which is significantly higher than the highest octane motor gasolines. For an Ed85 dedicated vehicle as opposed to the flexible fuel type, the higher octane number would permit a higher compression ratio and improved cycle efficiency.

Table 1-1. Octane Measurements for E80 (Ed85) (80% Ethanol, 20% Unleaded Gasoline).

Method	Octane Number
Research (R)	104.8
Motor (M)	99.3
(R+M)/2	102.1

Because water affects the octane number and the miscibility of ethanol in gasoline, the fuel blends were prepared with anhydrous ethanol. Desiccant breathers were installed on all opened fuel drums to prevent water from contaminating the fuel. The air breather tubes were closed when the fuels were not in use.

American Society for Testing Materials Standards for Ethanol Fuel Blends

American Society for Testing Material (ASTM) Committee D-2 on Petroleum Products and Lubricants is currently working on a new Standard Specification for Fuel Ethanol (Ed85-Ed70) for Automotive Spark-Ignition Engines. This specification defines different volatility classes for ethanol fuels throughout the U.S. based on geographic location and month of the year. The approach recognizes that the RVP of gasoline used in blending E80 should be increased to prevent problems with cold starting and driveability in cold weather. Southwest Research Institute is not directly involved in the ASTM effort, but the results of the study are important in the present project to define the fuel characteristics required for different cold-start conditions. This project may result in hardware that might reduce the fuel volatility requirement, but much work remains before that can be fully assessed. A draft copy of the proposed standard is attached as Appendix A.

Vapor Pressure Measurements and Correlations

Apparatus and Procedure

Vapor pressures were measured with a Grabner model CCA-VPS and a Grabner model CCA-VP equipped with Peltier cooler. A separate fluid cooling apparatus was used to help the Peltier cooler reach temperatures below -1°C (30°F). The instruments were calibrated with 2,2-dimethyl butane and n-pentane standards. Fresh blends of 5% and 15% by volume of n-butane, n-pentane, i-pentane, isomerate, diethyl ether, and UNLG with ethanol were prepared. Their vapor pressures were determined at -14.4°C (6°F), -1.1°C (30°F), 21.1°C (70°F), 37.7°C (100°F), and 54.4°C (130°F). The results of these vapor pressure measurements are shown in Table 1-2.

Figures 1-1 through 1-3 show Clapeyron-Clausius plots of the vapor pressure data for the ethanol blends in Table 1-2. Significant curvature is observed in most of the plots. For each fuel, the data were correlated according to the expression,

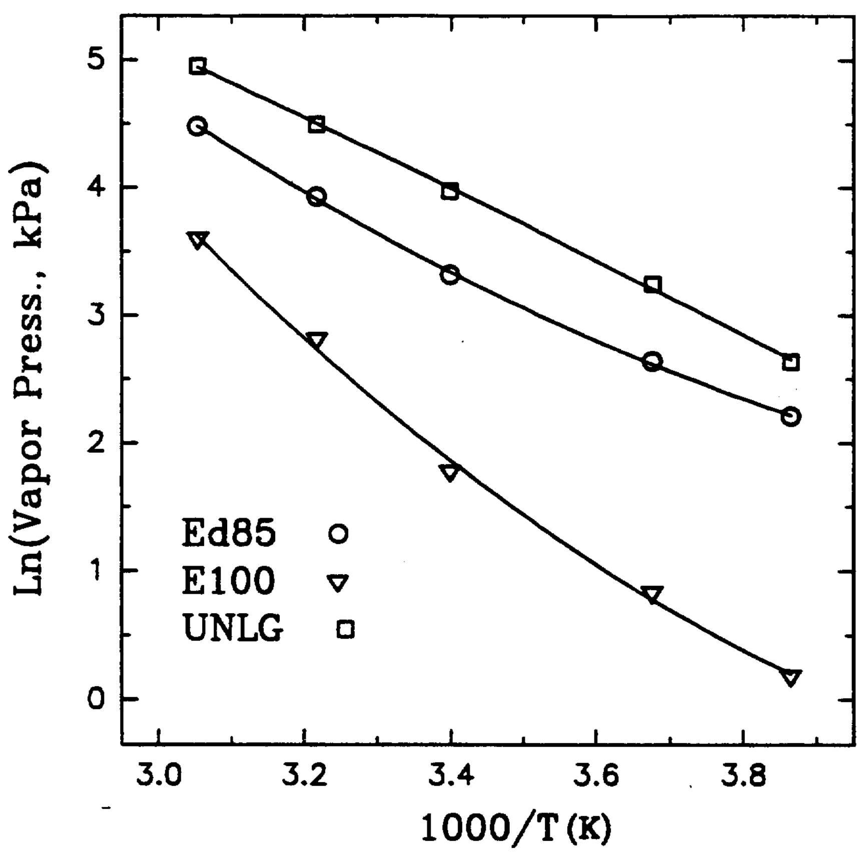

Figure 1-1. Effect of temperature on vapor pressure of ethanol/unleaded gasoline blends.

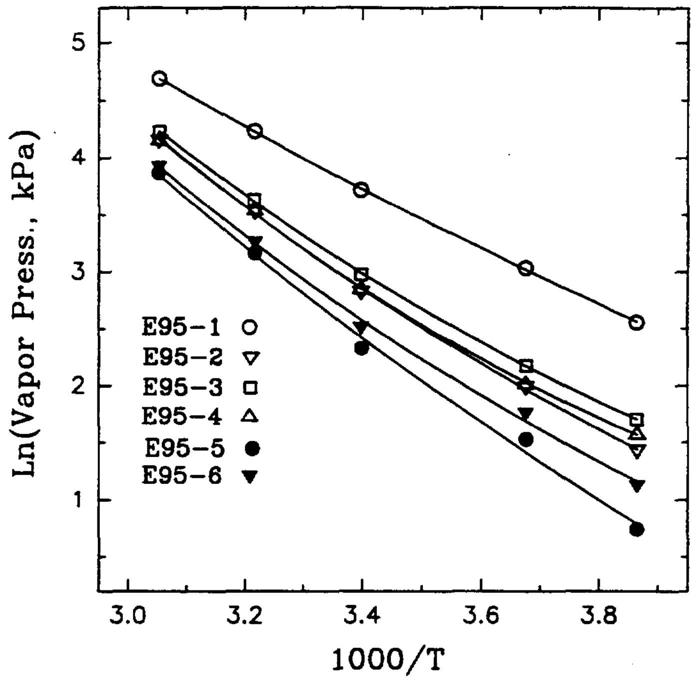

Figure 1-2. Effect of temperature on vapor pressure of E95 blends.

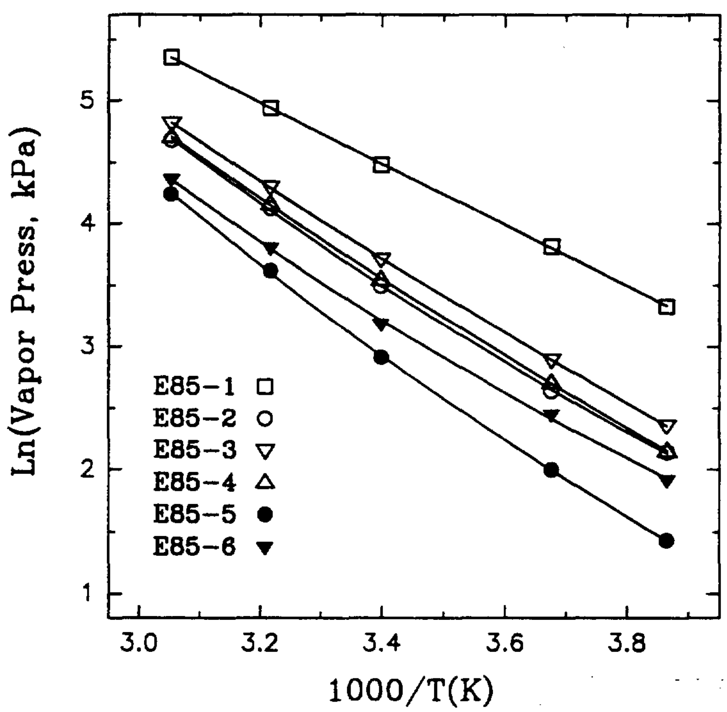

Figure 1-3. Effect of temperature on vapor pressure of E85 blends.

Table 1-2. Ethanol and Ethanol Blend Vapor Pressures as a Function of Temperature.

Sample (Sample Label)	Vapor Pressure, kPa (psi). @ Temperature, °C (°F) -14.4°C (6.0°F)	-1.1°C (30°F)	21.1°C (70°F)	37.7°C (100°F)	54.4°C (130°F)
E-80 (Ed-85)	12.6 (1.83)	14.0 (2.03)	27.6 (4.00)	50.8 (7.38)	88.1 (12.8
E-100	1.2 (0.17)	2.3 (0.33)	5.9 (0.86)	16.6 (2.41)	36.5 (5.29)
Unleaded Gasoline	4.0 (0.58)	25.8 (3.74)	53.3 (7.73)	89.8 (13.0)	141.8 (20.6)
85% Ethanol + 15% Component					
n-Butane (E85-1)	28.0 (4.06)	45.6 (6.61)	88.3 (12.8)	140.0 (20.31)	212.0 (30.7)
n-Pentane (E85-2)	8.5 (1.23)	14.0 (2.03)	33.1 (4.80)	62.0 (9.0)	108.1 (15.7)
Iso-Pentane (E85-3)	10.6 (1.54)	18.1 (2.63)	41.0 (5.95)	73.8 (10.7)	124.0 (18.0)
Isomerate (E85-4)	8.6 (1.25)	15.0 (2.18)	34.8 (5.05)	64.2 (9.32)	110.7 (16.0)
Di-Ethyl Ether (E-85-5)	4.2 (0.61)	7.4 (1.07)	18.4 (2.67)	37.4 (5.42)	69.5 (10.0)
Unleaded Gasoline (E85-6)	6.8 (0.99)	11.6 (1.68)	24.2 (3.51)	44.9 (6.51)	78.6 (11.4)
95% Ethanol + 5% Component					
n-Butane (E95-1)	12.9 (1.87)	20.8 (3.02)	41.1 (5.96)	68.6 (9.95)	108.5 (15.7)
n-Pentane (E95-2)	4.2 (0.61)	7.3 (1.06)	16.9 (2.45)	34.1 (4.96)	63.7 (9.24)
Iso-Pentane (E95-3)	5.5 (0.80)	8.8 (1.28)	19.7 (2.86)	37.8 (5.49)	68.4 (9.92)
Isomerate (E95-4)	4.83 (0.70)	7.5 (1.09)	17.3 (2.51)	34.6 (5.03)	63.7 (9.24)
Di-Ethyl Ether (E95-5)	2.1 (0.31)	4.6 (0.67)	10.3 (1.49)	23.7 (5.03)	47.7 (6.92)
Unleaded Gasoline (E95-6)	3.1 (0.45)	5.8 (0.84)	12.4 (1.80)	26.2 (3.81)	50.9 (7.38)

$$Ln(P_v) = A + \frac{B}{T} + \frac{C}{T^2} \tag{1-1}$$

where P_v is the vapor pressure, T is the absolute temperature, and A, B, and C are fuel dependent constants. Equation 1-1 is an extension of the Clapeyron-Clausius equation where the term, C/T^2, was added to account for the nonlinearity of the curves shown in Figures 1-1 through 1-3. Table 1-3 lists the parameters A, B, and C for the various fuels that have been examined.

Table 1-3. Correlating Parameters for Vapor Pressure Expressions: $Ln(P) = A + B/T + C/T^2$, Units: P in kPa, T in Degrees K.

Fuel Description	Code Name	A	B	C
Unleaded Gasoline	UNLG	11.34	-1,520.0	-1.878×10^5
Neat Ethanol	E100	38.36	-17,040.0	1.855×10^6
Ethanol - 20% UNLG	E80	37.98	-17,660.0	2.193×10^6
Ethanol - 15% n-Butane	E85-1	13.29	-2,692.0	3.050×10^4
Ethanol - 15% n-Pentane	E85-2	21.81	-7,541.0	6.340×10^5
Ethanol - 15% iso-Pentane	E85-3	18.06	-5,365.0	3.368×10^5
Ethanol - 15% C_5/C_6 Isomerate	E85-4	18.87	-5,817.0	3.856×10^5
Ethanol - 15% Diethyl Ether	E85-5	23.88	-8,768.0	7.661×10^5
Ethanol - 15% UNLG	E85-6	21.61	-7,751.0	6.879×10^5
Ethanol - 5% n-Butane	E95-1	16.49	-4,853.0	3.236×10^5
Ethanol - 5% n-Pentane	E95-2	25.21	-9,701.0	9.190×10^5
Ethanol - 5% iso-Pentane	E95-3	25.68	-10,110.0	1.012×10^6
Ethanol- 5% C_5/C_6 Isomerate	E95-4	28.55	-11,760.0	1.237×10^6
Ethanol - 5% Diethyl Ether	E95-5	24.45	-9,099.0	7.708×10^5
Ethanol - 5% UNLG	E95-6	26.57	-10,600.0	1.041×10^6

Curvature is caused by changes in the heat of vaporization with temperature and the effect of temperature on the solubility of the additive in ethanol. At lower temperatures, the nonpolar hydrocarbon additives become less miscible in ethanol so their vapor pressure dependence on concentration becomes more nonideal. Nonideal solutions have higher vapor pressures because the components act more independently to produce the observed vapor pressure. All ethanol-hydrocarbon solutions are nonideal, so lowering the temperature tends enhance that effect (make the solutions more nonideal). In contrast, the E95-5 and E85-5 blends of ethanol and diethyl ether have much lower vapor pressures than the ethanol-hydrocarbon blends because diethyl ether forms a nearly ideal solution with ethanol.

However, a more detailed analysis of the data involving parameters such as equivalence ratio, fuel-air ratio, and measured flammability limits was desired. The vapor pressure temperature correlations represented by Equation 1-1 are used with literature data on flammability limits to predict the upper temperature limits of flammability given in the next section.

Flammability Limit Data

Apparatus

The apparatus used in this study was similar to those used by Fanick et al. (1990) and Lawson et al. (1987) to measure flammability limits of fuel vapors. The combustion vessel shown in Figure 1-4 was a 500-mL three-neck round-bottom pyrex flask. The flask dimensions were sufficient to preclude wallquenching effects on the flammability limits (Zabertakis 1952; Coward and Jones 1952). The electrodes for ignition and the thermocouples for measuring fuel temperature were mounted in rubber stoppers that were placed in ports of the round bottom flask. The igniter electrodes consisted of two 10-cm lengths of 14-gauge copper wire mounted in parallel 12.7-mm apart in the stopper. The copper electrodes were sharpened to a point and bent at the ends to form a 2.5-mm spark-gap at the center of the flask. The electrodes were insulated with a polyethylene sheath up to where they were bent to form the spark-gap. An automotive spark coil capable of producing a continuous 400-Hz oscillating arc discharge was used to ignite the fuel vapors.

In fuel tanks, one ignition source of concern is a spark created by a triboelectric source charge accumulation in the fuel. Another source is a person charged with static electricity standing next to an open fuel tank. van Dolah et al. (1963) gave an interesting example; if an average-sized man with a capacitance of 300 pF builds up a charge of 10,000 volts, a discharge with an energy of 15 mJ could be initiated. From this standpoint, the automotive spark coil igniter, which produced a highly visible arc between the electrodes, was assumed to be an overwhelming ignition source.

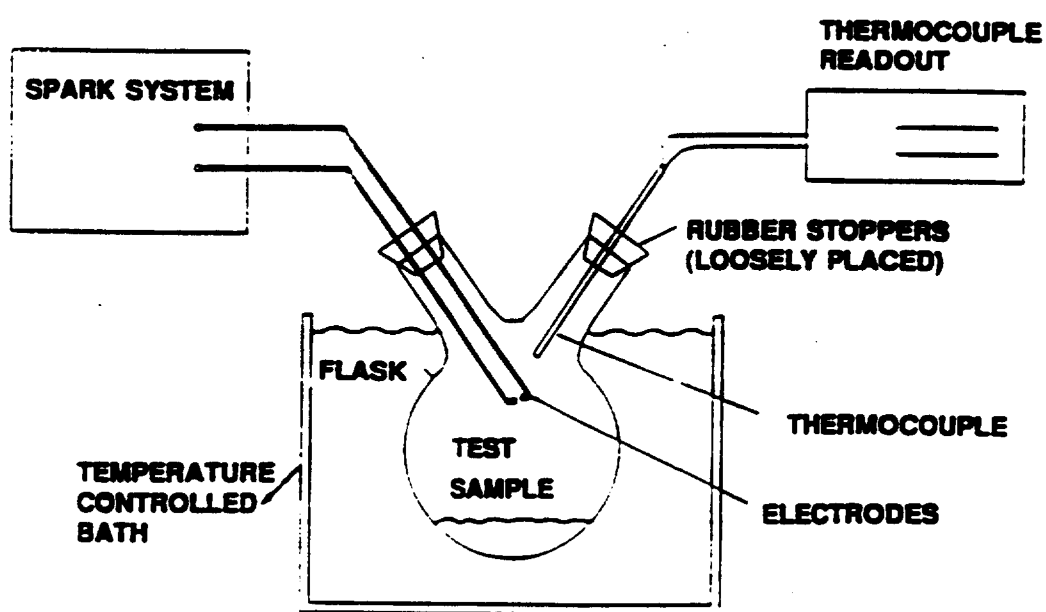

Figure 1-4. Flammability test apparatus.

Procedure

The combustion vessel was filled with 25 mL of test fuel. It was agitated to wet the walls of the flask so the fuel would evaporate and mix with the air. The flask was immersed in a constant temperature isopropanol/water bath controlled to within 0.5°C. It required about 30 minutes for the liquid fuel and bath temperatures to equilibrate. An attempt was made to ignite the fuel-air mixture about 20 minutes after the liquid fuel and bath temperatures reached equilibrium. The temperature limits of flammability were determined by trial and error.

At the start of testing, a presumed bath temperature was chosen. If ignition occurred at the chosen temperature, it would be characterized as weak, medium, or strong, depending on the aural (visual) intensity of the explosion. If the explosion was weak, the conditions were very close to the temperature limit of flammability. Therefore, in the next test the bath temperature would be raised just a few degrees. If no ignition occurred, the temperature limit was within a few degrees of the bath temperature in the last test. Once the temperature limit of flammability was bracketed to within a few degrees, tests were performed in 1°C increments to achieve accuracy to within 1°C.

Results

Rich and lean flammability limits were measured, and are presented in Table 1-4. Figure 1-5 shows the flammability results from Table 1-4 plotted versus the RVP, which is the vapor pressure measured at 37.7°C (100°F), from Table 1-2. The flammability limits correlate with the RVP, except those data that are tagged with labels. The labels in Figure 1-5 correspond with those defined in Table 1-2. The flammability limits may be predicted from the Reid vapor pressures except for the mixtures with n-butane, diethyl ether, and neat ethanol.

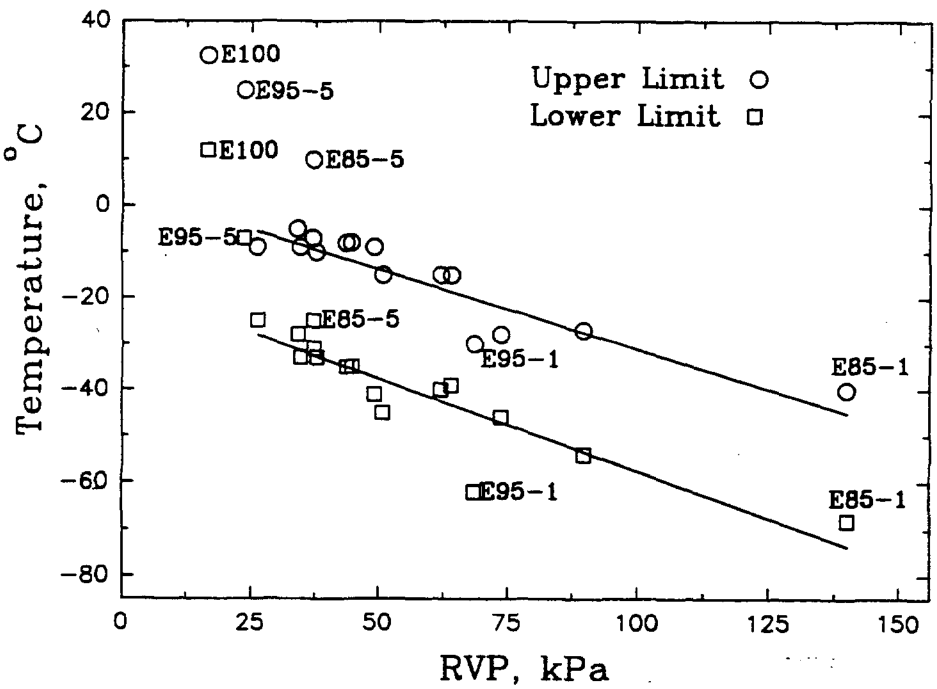

Figure 1-5. Temperature limits of flammability of ethanol blends containing 5% and 15% fuel additive.

The relationship between fuel vapor pressure and flammability limits was investigated further to determine how the flammability limits may be accurately predicted from the vapor pressures. This is important in estimating both engine cold startability and fuel tank flammability. N-butane shows a different flammability versus vapor pressure than the other mixtures because it forms a less ideal solution with ethanol; i.e., it does not follow Raoult's law for vapor pressures of mixtures. In contrast, the di-ethyl ether and ethanol form a relatively ideal mixture, which explains why ether blends do not show the same correlation of flammability limits versus RVP as the other blends. For the ethanol blends, much of the flammability is due to the hydrocarbon fractions.

For neat ethanol, only the ethanol vapors are available for combustion. Because of the different stoichiometry for ethanol combustion, more fuel vapor is required, which increases the temperature limit for flammable mixtures above that of the ethanol blends. The E100 and blends that contain n-butane and diethyl ether presumably deviate from the general dependence of temperature limit versus RVP because of differences in stoichiometry. As an example, the air-fuel ratio for stoichiometric combustion of gasoline is about 14.6, but ethanol is 9.01. The lean flammability limits for both materials are roughly at an equivalence ratio of 0.5, but this is an air-fuel ratio of about 29 for gasoline/air and 18 for ethanol/air mixtures.

Table 1-4. Ethanol/Ethanol Blends Flammability Test Results.

Sample	Flammability Limits	
	Upper °C (Rich)	Lower °C (Lean)
E80	-15	-45
E100	33	12
Unleaded Gasoline	-27	-54
85% ETOH + 15% n-Butane	-40	-69
85% ETOH + 15% n-Pentane	-15	-40
85% ETOH + 15% Iso-Pentane	-20	-46
85% ETOH +15% Isomerate	-15	-39
85% ETOH + 15% Di-Ethyl Ether	-10	-25
85% ETOH + 15% Unleaded Gasoline	-8	-35
95% ETOH + 5% n-Butane	-30	-62
95% ETOH + 5% n-Pentane	-5	-28
95% ETOH + 5% Iso-Pentane	-10	-33
95% ETOH +5% Isomerate	-9	-33
95% ETOH + 5% Di-Ethyl Ether	25	-7
95% ETOH + 5% Unleaded Gasoline	-9	-34

To account for variations in fuel composition, a simple computer model was written to use the vapor pressure measurements of the blends to estimate the molar ratios of ethanol and the additive, and then compute the equivalence ratio for the blends, accounting for the different fuel-air ratios required for the components. A computer code was written to calculate the upper and lower temperature limits of flammability from the vapor pressure and flammability limit data.

The calculations were performed by assuming that the partial pressure of ethanol, P_E, in the fuel blend is equal to,

$$P_E = X_E P_N \tag{1-2}$$

where X_E is the mole fraction of ethanol in the liquid phase, and P_N is the vapor pressure of neat ethanol. The partial pressure, P_A, of the fuel additive, e.g., butane, pentane, etc., was determined as,

$$P_A = P_{FB} - P_E \tag{1-3}$$

where P_{FB} is the vapor pressure of the fuel blend. The mole % of ethanol vapor, C_E, and additive vapor, C_A, were expressed as,

$$C_E = 100 \frac{P_E}{P_t} \tag{1-4}$$

and,

$$C_A = 100 \frac{P_A}{P_t} \tag{1-5}$$

where P_t is the total pressure, e.g., the atmospheric pressure.

Flammability limit data for neat ethanol and the pure components, n-butane, n-pentane, i-pentane, and diethyl ether were obtained from the literature (Hodgman 1957). The flammability limits of the vapors from unleaded gasoline were weighted about 70% butane and 30% pentane. The vapors from the isomerate were weighted about 70% pentane and 30% hexane. More accurate vapor compositions could have been determined by speciating the vapor space, but they were not.

Various approaches were used in combining the flammability limits of the components to arrive at the flammability limit of the ethanol-additive mixture. The following method of combining flammability limits was used. First, Equation 1-6 below was used to calculate the stoichiometric air-fuel ratios, AFR_{ST}, of the components.

$$AFR_{ST} = 4.76(x + y/4 - z/2) \tag{1-6}$$

The variables x, y, and z are the numbers of carbon, hydrogen and oxygen atoms respectively. The factors F_A and F_E were calculated via,

$$F_E = \frac{P_E AFR(E)_{ST}}{P_E AFR(E)_{ST} + P_A AFR(A)_{ST}} \tag{1-7}$$

and,

$$F_A = 1 - F_E \tag{1-8}$$

where $AFR(E)_{ST}$ and $AFR(A)_{ST}$ are the stoichiometric air-fuel ratios for ethanol and the additive. The flammability limit of the mixture, L_M, is then expressed as,

$$L_M = F_E L_E + F_A L_A \tag{1-9}$$

where L_E and L_A are the respective flammability limits of ethanol and the additive.

Finally, the temperature limit of flammability is determined when the Equation 1-10 below is satisfied.

$$L_M = C_E + C_A \tag{1-10}$$

Table 1-5 shows the upper temperature limits of flammability that were calculated by an iterative technique involving Equations 1-1 through 1-10. The calculations were performed by making incremental changes in temperature until the temperature satisfied condition of Equation 1-10.

Table 1-5. Comparison of Calculated with Measured Temperature Limits of Flammability.

Fuel Blend	Upper Temperature Limits of Flammability (°C)		Lower Temperature Limits of Flammability (°C)	
	Meas.	Calc.	Meas.	Calc.
E100	33	36.5	12	13.5
ULG	-27	-26	-54	-53
EtOH + 15% n-Butane	-40	-43.5	-69	-70
EtOH + 15% n-Pentane	-15	-16	-40	-56
EtOH + 15% Iso-Pentane	-20	-20	-46	-56
EtOH + 15% Isomerate	-15	-17	-39	-51
EtOH + 15% Diethyl Ether	10	12	-25	-29
EtOH + 15% ULG	-8	-8	-35	-49
EtOH + 5% n-Butane	-30	-26	-62	-62
EtOH + 5% n-Pentane	-5	4	-28	-37
EtOH + 5% Iso-Pentane	-10	-2	-33	-59
EtOH + 5% Isomerate	-9	2	-33	-106
EtOH + 5% Diethyl Ether	25	25	-7	-10
EtOH + 5% ULG	-9	15	-25	-23
EtOH + 20% ULG	-15	-17	-45	Error

* An error occurred in the iteration scheme for this fuel blend. This will be investigated further.

The results of the calculations were strongly dependent on the literature values of the flammability limits. For example, the flammability limits of ethanol given by Hodgman (1957) are 3.28 and 18.95 mole % in air. When these values are used, the calculated lower and upper limits of flammability are 6°C and 41°C respectively. The calculated limits for neat ethanol in Table 1-5 are based on lower and upper flammability limits of 4.4 and 14.3 mole % respectively measured in a combustion bomb (Naegeli and Weatherford 1989).

A similar problem arises in computing the temperature limits of the ethanol/diethyl ether blends. Hodgman (1957) gives flammability limits of 1.85 and 36.5 mole % in air for diethyl ether. The lower limit of 1.85 seems reasonable, but the measured upper temperature limits indicate that the upper flammability limit of diethyl ether is much lower than the literature value. Rich limits in the literature are often too high because they include cool flame reactions that give rise to chemiluminescence when there is no heat release or pressure rise accompanying the ignition process. The calculated values in Table 1-4 for the ethanol/15% diethyl ether and ethanol/5% diethyl ether blends were determined assuming that the upper flammability limit of diethyl ether is 12.5 mole % in air. This is substantially lower than the literature value of 36.5 mole %. Hence, from the standpoint of fuel tank flammability, we recommend that the flammability limits of diethyl ether and probably several other oxygenates should be reexamined.

There was good agreement between measured and calculated upper and lower temperature limits of UNLG, E95, ethanol/15% n-butane and ethanol/5% n-butane blends. The agreement was good between measured and calculated upper limits, but poor between the lower limits of E85, and the blends of ethanol with 15% n-pentane, iso-pentane, and isomerate. The agreement was poor in upper and lower temperature limits of the ethanol blends containing 5% n-pentane, iso-pentane and isomerate. For the upper temperature limit, the problem seems not to be in the flammability limits of the additives, n-pentane, iso-pentane and isomerate, because the agreement was good in the 15% blends. However, the calculated lower temperature limits were well below the measured limits for both the 5% and 15% blends of ethanol that contained n-pentane, iso-pentane and isomerate. Increasing the lower flammability limits of n-pentane, iso-pentane, and isomerate by 30% made an improvement of only a few degrees in the calculated lower temperature limits. Because the literature values of the lower flammability limits are relatively accurate, the problem seems to be related to the accuracy of the vapor pressure expressions (see Equation 1-1).

Because of the curvature in the Clapeyron-Clausius plots of vapor pressure versus temperature, there is some question of the accuracy of the low temperature data. If there are inaccuracies in the database, extrapolations of vapor pressures to temperature beyond the range of the database could yield erroneous vapor pressure values. To resolve the problem, we recommend that the vapor pressures be rerun on freshly blended mixtures of E80 and all the ethanol blends.

Fuel Lubricity

Fuel lubricity was measured with a Ball on Cylinder Lubrication Evaluator (BOCLE). In the BOCLE test, a steel ball locked in a fixed position rides on a rotating steel cylinder that is immersed in the test fluid. The contact frictional load between the ball and cylinder is controlled by a weight applied to a lever that forces the ball against the cylinder. The wear rates are measured in terms of the diameter of the wear scar on the steel ball. The wear scar is elliptical so its diameter is determined as the average of its width and length. Fuel lubricity is inversely proportional to the wear scar diameter.

In the standard BOCLE procedure, the test fluid is purged with room temperature air at a relative humidity of 10%. Purging with air is applicable to lubricating oils and middle distillate fuels, but is seldom used with volatile fuels such as gasoline, ethanol, and ethers. It causes the fuel to evaporate and cool, and in some instances, fuels such as alcohols extract a large amount of water from the air. Because water has a significant effect on wear in the BOCLE test, there was no air purging of the ethanol and gasoline blends examined in the present study.

The results shown in Table 1-6 are interesting in that the wear scar diameter for ethanol is less than that for UNLG gasoline. Intuitively, it would seem that gasoline, which contains relatively high molecular weight hydrocarbons, would be a better lubricant than ethanol. There are various theories why ethanol is a better lubricant. One explanation is that ethanol's relatively high polarity causes it to adhere to the metal surface and act as a protective cushion.

Table 1-6. Fuel Lubricity Determined from Wear Tests with the Ball on Cylinder Lubrication Evaluator.

Fuel Blend	Wear Scar Diameter, mm
UNLG	0.60
Ethanol + 20% UNLG	0.59
Ethanol + 15% UNLG	0.53
Ethanol + 5% UNLG	0.52
Neat Ethanol	0.50
Neat Methanol	0.44

An alternative theory assumes that ethanol has a higher resistance to oxidation than the hydrocarbons in gasoline. Tribologists conclude that very high lubricant temperatures are produced in the wear zone when aspirates on the metal surfaces make contact. The fuels almost always contain some dissolved oxygen, so the high temperatures cause the fuel to autoxidize. Corrosive substances such as peroxides and carboxylic acids may be among the oxidation products.

Wear rates usually decrease dramatically when dissolved oxygen is removed from the test fluid. If the test fluid is thoroughly purged with nitrogen to remove the dissolved oxygen before the test, and also purged with nitrogen throughout the test, the wear scar is greatly reduced.

Table 1-7 shows the results of recent experiments performed to determine the effect of removing oxygen on the lubricity of alcohols. The nitrogen and air used in the tests were preconditioned with 10% relative humidity at room temperature. The alcohols were absolute water free at the start of the test, but no doubt absorbed a significant amount of water during the test. Methanol and ethanol literally extract moisture from the air; the effect is much less with propanol, and relatively weak with butanol. The experiments "with air" and "with nitrogen" were performed in the same way so the effect of humidity on both tests was the same.

Table 1-7. Ball On Cylinder Lubrication Evaluator Tests on Alcohols with and without Oxygen.

Alcohol Fuel	Type of Aeration	
	With Air	With Nitrogen
Methanol	0.53	0.51
Ethanol	0.83	0.47
Propanol	0.72	0.56
Butanol	0.66	0.50

Oxygen had little or no effect on the lubricity of methanol, but lubricity increased in jet fuels and diesel fuels when the oxygen was removed. The effect of dissolved oxygen on the other alcohols, particularly ethanol, was substantial. Preliminary work has shown that methanol has a relatively high oxidation stability. Because ethanol is more akin to a hydrocarbon, it probably has a lower oxidative stability than methanol. Theoretically the oxidation products such as peroxides and carboxylic acids cause metal corrosion, which enhances the wear process.

In conclusion, the lubricity of neat ethanol compares favorably with gasoline, but contamination with water and dissolved oxygen exacerbates the wear in ethanol more so than in gasoline.

Task 2 Fuel Storage and Handling System Design

Objective

The objective of this task was to evaluate material compatibility issues, and specifically to examine ethanol- related wear in fuel injectors.

Discussion of Material Compatibility Issues

Bourn et al. 1994 listed the materials in the fuel system of the 1993 Ford Taurus FFV, and discussed compatibility with ethanol and ethanol/gasoline blends. The original intent of this task was to ensure that the materials would be compatible with ethanol and ethanol blends through testing and discussions with material experts.

Because of the new enhanced evaporative emissions regulations, many fuel line components used in current FFV, such as the 1993 Ford Taurus FFVs purchased for this project, will not be suitable in future vehicles. For example, fuel lines and elastomers in o-rings in current FFVs have high enough permeability that they will not pass the enhanced evaporative emissions test, according to Ford engineers. Therefore, durability testing with these components, as originally proposed, is no longer suitable. The new materials that will pass enhanced evaporative emissions standards are either still being developed or are proprietary, and are not available for testing. This section summarizes some areas where new materials are required.

Ford staff members were consulted about materials currently used in the Taurus FFV and material changes Ford is making to meet the enhanced evaporative emission standards. Most current materials are unsuitable for the more stringent requirements of the enhanced evaporative standard, and Ford is replacing them with more suitable materials. Several areas are discussed below.

The current fuel tank is a high-density polyethylene with a fluorinated interior surface. This tank will not meet the new standards, and future vehicles will be fitted with a metal tank that may be coated with a plastic or polymer.

Flexible fuel lines used to connect the fuel tank to the fuel lines are a potential problem for evaporative emissions. These lines must be flexible and have 150% elongation to be crash worthy. Many materials that have the flexibility are permeable and sources of evaporative emissions. The solution to these problems is not known at this time.

Fuel line connectors are sealed using viton o-rings with a high fluorine content. These o-rings have permeability problems. Ford is currently investigating several materials to replace viton in the fuel system. At this time these materials are proprietary.

O-rings and seals currently in the fuel system have been acquired for compatibility testing. Data for elastomer swell for many of the materials have been found, and were included in the design report (Bourn et al. 1994).

The enhanced evaporative standard is apparently forcing the use of new materials. Therefore, the value of testing the current materials is unclear.

Two components that often give trouble in FFVs are the fuel pumps and the fuel injectors. Although occasional problems have been reported in earlier FFVs when the vehicles are operated on methanol (for which the fuel system was designed), very few problems have been reported with ethanol.

Fuel Injector Wear Testing

For the above reasons, the focus of the durability testing for this task has been shifted from overall fuel system durability testing to testing fuel injectors and fuel pumps that are not expected to require materials changes for enhanced evaporative emissions. The interest in testing the fuel pumps is strictly durability, but the interest in testing the fuel injectors is fuel leakage and injector performance degradation. There is much current interest in gasoline-fueled engines in leakage past the fuel injector seats when the engine is turned off and the fuel line remains pressurized. The line must remain pressurized to avoid vapor lock (fuel boiling in the line during heat soak-back). Any fuel leaking past the valve seat collects in the intake port and manifold, and introduces a large hydrocarbon spike on the next start-up. This cannot be corrected with fueling strategy, because the amount of leakage is unknown and the engine must be fueled sufficiently to start on the first cylinders to receive fuel.

Researchers must determine whether the ethanol fuel injectors begin to leak more after some usage, and whether they are better or worse than gasoline injectors in their leakage and wear characteristics. A test plan was developed in Phase 2 for these tests based on SAE Procedure J1832 (attached as Appendix B). The testing will be conducted during Phase 3. This procedure provides some guidelines for performing the injector leak rate test, but it also leaves significant room for variations in test procedures between different laboratories.

Several industry sources have suggested that alcohol fuels can affect the durability and performance of fuel injectors. In particular, injectors have been subject to erosion and wear of the nozzle seat and orifices resulting in variation in fuel flow and injector leakage. Experiments will be conducted on E100 and E80 fuels to evaluate their effects on fuel injector performance and durability. As a baseline for comparison, a national average gasoline will be used. The experiments will be conducted in accordance with SAE J1832.

SAE Standard J1832 specifies test procedures for evaluating gasoline fuel injectors. It covers all aspects of the fuel injectors, including spray distribution and coil dynamics, but only the static flow rate, the dynamic flow, and the seat leakage rate are typically of interest for durability experiments. The static flow rate is the maximum flow of the injector and is achieved when the injector is energized in the fully open position. The dynamic flow is the measured fuel delivered per pulse of the injector when energized at 2.5-ms pulse width (PW) and a 10-ms period.

Test Plan for Fuel Injector Wear Testing

Test Fuels: The injectors will be evaluated on E100, E80, and a national average gasoline. For performance testing, a standard calibration fluid will be used as the test fluid.

Injectors: Fuel injectors from the Ford Taurus will be used. A minimum of 18 injectors will be tested, six injectors for each fuel.

Performance Parameters: Each injector will be evaluated for static flow rate, dynamic flow, and seat leakage.

Test Duration: The injectors will be operated for approximately 900 million cycles at a 2.5 ms PW and 5 ms period.

Frequency of Performance Checks: Each injector will be evaluated according to the following schedule:

0 cycles
100 x 10^6 cycles
At 100 x 10^6 cycle intervals until the end of testing.

Alternative Fuels Refueling Conference and Trade Show

On March 17 and 18, 1994, Terry Gray attended the Alternative Fuels Refueling Conference and Trade Show put on by the Petroleum Equipment Institute (PEI) in Orlando, Florida. Technical sessions included discussions of refueling/distribution equipment interface requirements, problems, and successes with each of the alternative fuels (LPG, methanol, ethanol, CNG, and LNG).

More than 700 people attended, representing manufacturers, distributors, installers, and fuel distributors. Most of the exhibits were related to CNG, but alcohol fuel tolerant equipment was shown by several manufacturers of pumps and dispensing equipment. Separate conversations with representatives of Goodyear (hoses), Ford, and the California Energy Commission, as well as information from the sessions, indicated some remaining compatibility issues. However, there was the strong feeling that, once identified, the problems would be solved by the companies involved.

There was also the caution to look at compatibility not only from the standpoint of the fuel's effect on the material, but also from how the fuel might be affected by the interaction. An example is the sensitivity of aluminum to the alcohol fuels, which results not only in corroded aluminum parts, but also in plugged filters and injectors from the aluminum compounds in the fuel.

A significant number of independent fuel distributors in the Midwest install ethanol fuel dispensers in addition to federal, state, and regional programs, so contact with these groups will provide important feedback to this program.

Task 3 Engine System Assembly and Testing

Objectives

There were several objectives of task 3 of Phase 2. First, the 3.0-liter engine needed to be removed from the Ford Taurus FFV, and modified as determined during Phase 1, and detailed in the design report (Bourn et al. 1994). Second, the modified engine had to be mounted in the test cell that had been modified with the addition of a refrigerated chamber. Third, the SwRI RPECS engine controller hardware and software had to be developed sufficiently to perform steady-state testing and cranking/start-up tests. The final objective was to determine minimum timing advance for best torque (MBT) timing, volumetric efficiencies, and other parameters needed by the engine controller, as well as to begin determining start-up strategies.

Engine Test Cell Setup

Because low-temperature cold-starting is an important issue with alcohol-fueled engines, a refrigeration system and cold box were installed in the test cell. The cold box originally planned for this project was not serviceable, so a new cold box was used along with the existing compressors and heat exchangers. Significant problems have been encountered with leaks in the refrigeration system, but the system with engine installed routinely reached -18°C (0°F), and on some occasions lower temperatures.

The test cell was set up to accommodate the refrigerated chamber 3.0 m x 3.0 m x 2.4 m (10 ft. x 10 ft. x 8 ft.) with the engine installed inside the chamber. The engine cooling system was set up with two completely independent cooling loops. The first cooling loop was used for low-temperature cold starts and consisted of a radiator and fan inside the refrigerated box, a pump to circulate the water even with the engine stopped, and the necessary plumbing. The second system was used for steady-state testing at higher power conditions and used a heat exchanger to cool the engine coolant with water tower cooling water. The engine water pump was used to circulate water in this cooling loop. Thus, the first cooling loop cooled the engine to very cold temperatures for cold starting and low power operation, but could not maintain cold temperatures at higher engine powers. The second loop was the standard cooling loop that could maintain any engine temperature from about 35°C (95°F) to 120°C (248°F) or higher.

The engine is a 3-liter V-6 Ford adapted to run on M85 or gasoline, or any mixture of the two. The principal modifications by the OEM from the gasoline engine include higher flow rate injectors that have materials suitable for alcohol fuels, an extra starting injector that provides high flow rates for low-temperature starts, and a different ignition system that uses a 36-tooth gear and solid-state ignition. This engine was removed from a vehicle that included an automatic transmission, but it was desirable for test cell operation to include a clutch between the engine and the dynamometer. Unfortunately, the engine block casting is different for Ford 3.0-liter engines that are to be used with automatic and manual transmissions. Therefore, a standard bell housing and clutch cannot be attached to a Ford 3.0-liter built for an automatic transmission. These components had to be constructed that would mate with the existing engine. The clutch is operated with an air solenoid, so the engine may be started without any load, but the load is applied after start-up. The engine is connected through the clutch to a dynamometer and an electric motor. The dynamometer is used to absorb the load from the engine, and the electric motor to motor the engine for various testing.

Fuel flow is read with a MicroMotion Coriolis mass flowmeter. Because Coriolis forces respond to mass flow, the output is not affected by the fuel density, pressure, or temperature. A significant fraction of the fuel that flows to the engine is recirculated to the fuel tank, so several pressure regulators and an extra fuel loop were used to measure only the fuel being used by the engine. Both the instantaneous and cumulative fuel mass flows measured by the MicroMotion can be compared with the calculated fuel mass flow in the RPECS engine controller that is derived from the fuel injector pulse width and the fuel differential pressure, with a correction for battery voltage, which affects the injector opening time. These flow rates typically agree to within 10 % or better. Because the fuel can heat up by recirculating through the system if the fuel pump is on but the engine is not running, a heat exchanger with cooling tower water is used to maintain a constant fuel temperature.

Air flow into the engine is measured three different ways. A laminar flow element (LFE) is part of the test cell instrumentation and is sampled as part of the low-speed data acquisition, and is also fed to the RPECS engine controller. The production engine is supplied with a hot-wire mass air flow (MAF) sensor. This signal is filtered using a pi filter as suggested by Ford, and is fed to the RPECS engine controller. The engine has also been fitted with a manifold air pressure (MAP) sensor (a GM production MAP sensor), and this is used to compute air flow by a standard speed-density calculation. A speed-density calculation of air flow multiplies engine speed by engine displacement, volumetric efficiency, and air density in the intake manifold.

The LFE air flow measurement provides an accurate reference for steady-state air flow, but cannot be used on the vehicle. The MAF sensor and the speed-density calculations can be used to compute air flow on the vehicle, with each having advantages and disadvantages compared to the other. The speed-density calculation based on the MAP sensor computes air flow at the intake valves, which is where the fuel is injected and therefore gives a more accurate measure of the air flow to meter the fuel. In contrast, the MAF sensor measures air flow at the throttle plate. However, because the MAF measures air flow upstream of the MAP sensor, it provides some lead-time information that is helpful in transients. In addition, the MAF sensor provides some serendipitous transient fueling compensation, since on tip-ins (accelerations) the intake manifold filling event causes an instantaneously higher flow rate of air at the throttle plate than at the valves. This helps to compensate for the fact that not all the fuel injected makes it directly into the cylinders, as some of it hangs up on the walls.

In addition to these three independent measurements of air flow, a calculation of air flow will be added in the RPECS engine controller based on throttle angle, pressure differential across the throttle plate, and discharge coefficient of the throttle plate as a function of throttle angle and pressure differential. This will be used to compute air flows and manifold air pressure, and it should be possible to compute the values with low noise faster than they can be measured. This is very important to transient compensation.

Engine Modifications

Bourn et al. (1994), described three modifications as planned for the Ford 3.0-liter engine. All three were carried out as planned. First, the compression ratio was raised from 9.3 to 11.0 by removing some material from the head and from the block, and by including a dome on the piston. Detailed drawings and dimensions were provided in the Design Report, and some of those procedures are also summarized below. Second, air-assist injectors as previously described were mounted onto the engine. Some atomization results are provided below. Third, because of the other engine modifications, the engine could not be operated using the standard Ford EEC IV engine controller. Therefore, a SwRI RPECS was developed for the 3.0-liter engine. Many details of the RPECS control system were described in the Design Report, and further details are provided under Task 6 of this report.

Increased Compression Ratio

The engine was removed from the vehicle, disassembled, and modified to increase the compression ratio from 9.3 to 11.0. This modification was to take advantage of the very high octane number of ethanol by improving the cycle efficiency. Typical efficiency increases are 3% per one unit of compression ratio. The cooling effect of ethanol is also predicted to improve the cycle efficiency by reducing compression work.

Figure 3-1 shows the dimensions of the Ford 3.0-liter reciprocating components and combustion chamber. Table 3-1 shows the calculations based on these dimensions for increased compression ratios. The piston face-to-block deck clearance was 0.49 mm (0.019 in.) which was reduced by milling the block surface, achieving a zero deck height and removing 3.07 cc (0.187 ci) from the clearance volume. The original cylinder head combustion chamber volume was measured to be 49.6 cc (3.03 ci), and Table 3-1 gives compression ratios corresponding to volume removed from the chamber when the head was milled 0.71 mm (0.040 in.). Calculations were performed for reducing the clearance volume by machining the cylinder head and block gasket surfaces the maximum safe amount.

Table 3-1. Ford 3.0-liter FFV - Cylinder Modifications.

Original Dimensions		Modified Dimensions	
Combustion Chamber Volume	48.56 cc	Mill Head 0.71 mm (0.028 in)	45.06 cc
Head Gasket Volume	7.69 cc		7.69 cc
Piston-to-Deck Volume	3.07 cc	Mill Block 0.49 mm (0.019 in)	0 cc
Ring Crevice Volume	0.58 cc		0.58 cc
Valve Relief Volume	0.34 cc		0.34 cc
Piston Dome Volume	0 cc	1.01 mm (0.040 in) height	-4.0 cc
Clearance Volume	60.24 cc		47.42 cc
Swept Volume	498.13 cc		498.13 cc
Compression Ratio	9.27:1		**11.03:1**

A maximum compression ratio of approximately 10.4:1 can be achieved by the machining procedures alone. The target compression ratio of 11:1 was achieved by adding pistons with a small dome volume of 4.0 cc (0.244 ci). The combination of cylinder head and block machining and pistons with a very small dome achieved the desired compression ratio for increased engine efficiency while minimizing the quench volume. However, although the increased compression ratio should increase engine efficiency, the hydrocarbon and nitric oxide emissions are expected to increase, making it more difficult to meet ULEV targets. The tradeoff between efficiency and emissions by adjusting compression ratio is fundamental, and therefore, difficult to avoid.

Air-Assist Fuel Injectors

Air-assist injectors were constructed for this project by fitting fuel-air mixing caps over the OEM FFV fuel injectors. The OEM fuel injectors are pintle injectors suitable in materials of construction and flow rate for alcohol-fueled engines. Fueling rates for M85 are about twice that of gasoline, and fueling rates for ethanol are about 1.6 times that of gasoline. Because the OEM injectors were designed for M85, their flow capacity is oversized for ethanol fuels, but can meet the maximum flow rate requirements.

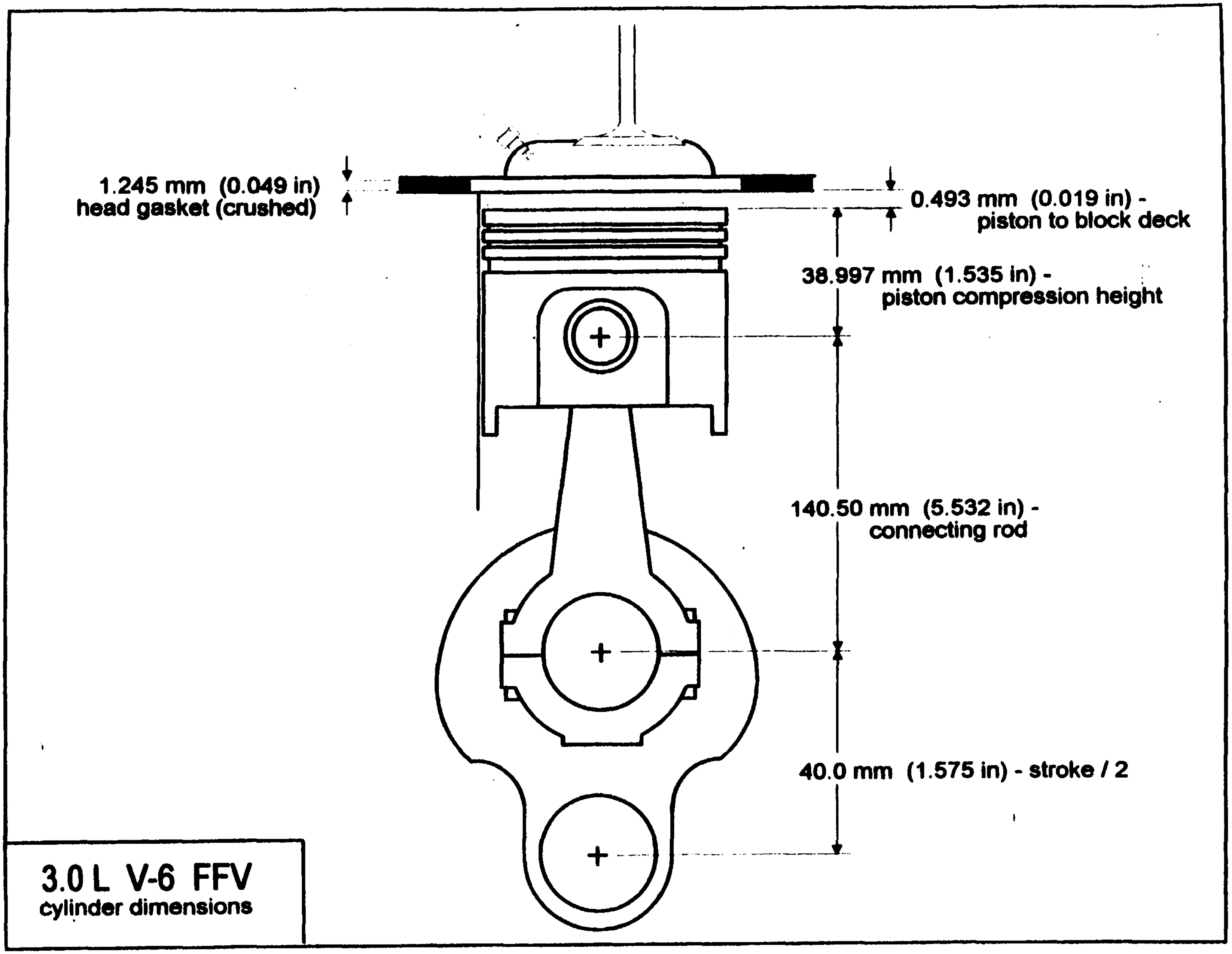

Figure 3-1. Piston and combustion chamber for Ford Taurus 3.0-liter V-6.

The fuel-air mixing caps were designed to be used in the standard manifold. However, the injectors had to be raised slightly to accommodate the mixing caps, and this resulted in interference with the intake manifold on one side of the engine. Therefore, a spacer of about 8.1-mm (0.319 in.) thick was added to the intake manifold to provide sufficient clearance for the injectors with the caps. Also, the mounting brackets for the fuel rail had to be modified to account for the slightly raised position of the OEM fuel injectors when the fuel-air mixing caps were added.

A schematic of the fuel-air mixing caps is shown in Figure 3-2. The caps were designed such that the principal air pressure drop is across the 1-mm exit hole from the injector. Therefore, this is an internal-mix, air-assist injector design. They have been tested with and without fuel-impingement screens that have been found useful in other injectors. The results reported here are for the design with the impingement screens.

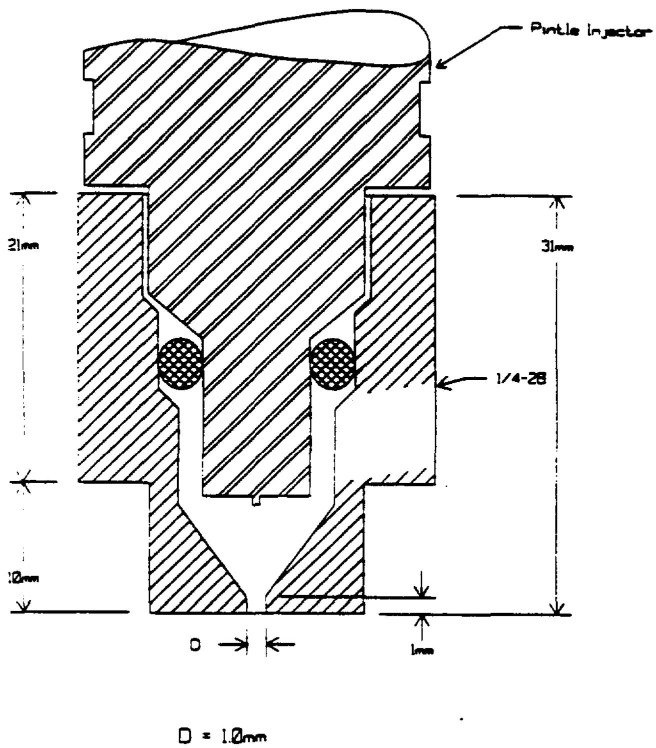

Figure 3-2. SwRI internal-mix air-assist injectors.

Figure 3-3 shows the Sauter mean diameters (SMDs), or surface area-volume mean diameters for three different pulse widths. The pulse width of 3-ms corresponds to an idle condition, 4-ms to a cruise, and 10-ms to an enriched pulse for acceleration or start-up. Compared with the OEM injectors that produce SMDs of about 120 µm , these injectors produce very fine sprays that will follow the air stream into the cylinder better and evaporate faster than fuel drops from the OEM injectors. However, at all conditions, but especially the 10-ms pulse width, the SMDs are somewhat larger than expected. The relatively poorer performance may result from the much higher flow rate of the fuel injector for the FFV compared to a gasoline injector (sized for more than twice the static flow rate of a gasoline injector, as required for methanol). Another factor is the smaller hole used in the fuel-air mixing cap than on some previous designs. A fuel injector with a smaller static flow rate would still be sufficient for ethanol (but not methanol), but the FFV injectors with materials suitable for alcohols are generally sized for methanol. Larger exit holes on the fuel-air mixing cap improves atomization at the cost of higher air consumption, and therefore, higher fuel usage to generate the power required by the air pump.

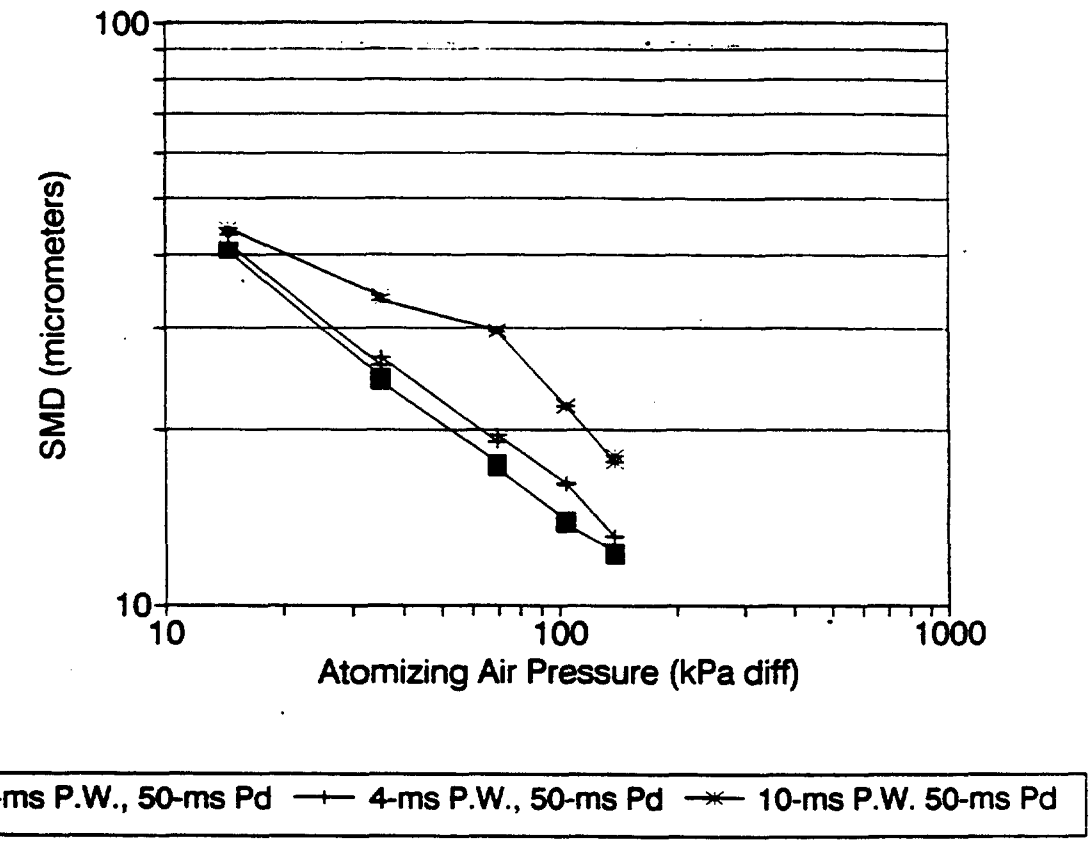

Figure 3-3. Effect of atomizing air pressure on average drop as represented by SMD (D_{32}), standard Taurus 3.0-liter flexible fuel injector and fuel-air mixing cap with 1-mm exit hole.

In addition to the atomization characteristics, the fuel delivery characteristics of the injectors are important. Fuel delivery characteristic refers to how quickly and completely the fuel exits from the fuel-air mixing chamber. If there are lags in the fuel delivery, cycle-to-cycle variability for the fuel delivered to the cylinder can be encountered, which results in cycle-to-cycle variations in air-fuel ratio and in power (IMEP). These characteristics will be examined later in the project.

Rapid Prototyping Engine Control System Engine Controller

Because of the other modifications to the engine described above, we could not use the OEM Ford EEC IV engine controller. Therefore, SwRI adapted an RPECS to the Ford Taurus 3.0-liter engine for complete authority engine control. The cost for hardware and software development was paid mostly from Task 3 funds, but is discussed under Task 6 below.

Task 4 Emissions Control System Development and Testing

Objectives

The objectives of this task were to perform FTP emissions tests on the baseline 1993 Ford Taurus FFV on Ed85 (E80), to modify that vehicle for advanced aftertreatment devices, and to perform the first set of FTP emissions tests on the vehicle with advanced aftertreatment devices.

The following section details the exhaust emissions control efforts undertaken in this program, including:

- Baseline emissions tests
- Advanced aftertreatment system characteristics
- Modifications to vehicle for installing of aftertreatment systems
- Emissions results with electrically heated catalyst/reformulated main catalyst systems
- Future plans

Baseline Emissions Tests

Southwest Research Institute received two Ford Taurus FFVs in March, 1994. One was designated for use in the emissions control system design task. This vehicle was delivered with 18 miles on the odometer. The oil was replaced with Pertolube purchased for this program, and a new oil filter was installed. The fuel system was drained, and the vehicle was fueled with E80. The vehicle was then driven for 4,000 miles over a modified Automobile Manufacturers Association durability driving schedule before baseline emissions tests were conducted.

Duplicate tests were conducted on the vehicle both with and without a catalytic converter to establish baseline exhaust emissions levels. The vehicle was operated over the chassis dynamometer portion of the Federal Test Procedure (FTP) for light-duty vehicles while operating on E80. Results of these tests are presented in Table 4-1.

Table 4-1. Baseline Federal Test Procedure Exhaust Emissions from Ford Flexible Fuel Vehicle.

Exhaust Constituents	Without Catalyst	With Catalyst	TLEV	ULEV
THC[a] (g/mi)	2.75	0.21		
CO (g/mi)	12.71	1.90	3.4	1.7
NO_x (g/mi)	2.03	0.10	0.4	0.2
CH_4 (g/mi)	0.09	0.05		
NMHC[b] (g/mi)	0.83	0.06		
Carbonyls[c] (g/mi)	0.41	0.02		
Alcohols[d] (g/mi)	1.43	0.09		
Estimated NMOG[e] (g/mi)	2.663	0.160		
Est NMOG x RAF[f] (g/mi)	1.784	0.107	0.125	0.040
Formaldehyde (mg/mi)	122.80	1.54	15	8
Acetaldehyde (mg/mi)	266.93	12.87		

[a] THC = NMOG + CH4
[b] Gasoline derived NMHC = FIDHC - (CH_4 x FIDRCH4) - (Ethanol x FIDRETH); FIDHC - hydrocarbon measured with flame ionization detector calibrated on propane; FIDRCH4 - FID response factor for methane; FIDRETH - FID response factor for ethanol
[c] Summation of all measured aldehydes and ketones including: formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, isobutyraldehyde + methyl ethyl ketone, and hexanaldehyde
[d] Ethanol only; no methanol was found in exhaust samples
[e] NMOG = NMHC + Carbonyls + Alcohols
[f] RAF = 0.67 as measured by Kroll at Volkswagen (SAE 932676)

Exhaust samples were measured for HC, CO, NO_x, CH_4, aldehydes and ketones, and alcohols (only ethanol was detected). Nonmethane organic gases (NMOG) were estimated using NMHC from the gasoline portion of the fuel as measured by a flame ionization detector (FID) rather than by hydrocarbon speciation. Gasoline-derived NMHC was determined by measuring hydrocarbons with a FID calibrated on propane, then correcting the results for the removal of CH_4 and ethanol.

These data show the unmodified vehicle meets TLEV exhaust emissions standards, and that the vehicle catalyst is quite effective in reducing all exhaust constituents. These low emissions levels were obtained even though the vehicle was calibrated for low emissions on M85 or gasoline, but not on ethanol blends. To better demonstrate where improvements could be made in the efficiency of the catalyst, selected individually weighted emissions for each phase of the FTP are presented in Table 4-2.

Table 4-2. Weighted Baseline Federal Test Procedure Exhaust Emissions for Ford Flexicble Fuel Vehicle with Catalyst.

Exhaust Emission	Individually Weighted Exhaust Emissions (g/mi) Bag 1A (0-140 sec)	Bag 1B (141-505 sec)	Bag 2	Bag 3	Total Weighted FTP Emissions (g/mi)	Bag 1A Percentage of Total NMOG Emissions
NMHC	0.04	<0.01	<0.01	0.01	0.06	27%
Ethanol	0.09	<0.01	<0.01	<0.01	0.09	56%
Acetaldehyde	0.01	<0.01	<0.01	<0.01	0.01	10%

These data show that unburned ethanol in Bag 1A (first 140 seconds of FTP) accounts for 56% of all FTP NMOG emissions, and acetaldehyde in Bag 1A accounts for approximately 10% of all NMOG emission.

In addition, Bag 1A NMHC emissions contribute 27% to total NMOG. Thus, approximately 93% of all NMOG emissions from this vehicle occur in the first 140 seconds of the FTP, of which 66% are caused by unburned ethanol and acetaldehyde. These data suggested the need for supplemental catalyst heating at vehicle start, to quickly light off the catalyst. In addition, the main catalyst needed to be formulated to specifically target unburned ethanol and acetaldehyde.

Modifications to Vehicle

To improve the exhaust emissions from the test vehicle, an electrically heated catalyst was obtained from WR Grace, and a main catalyst specially formulated for operation on alcohol vehicles was obtained from Degussa. A summary of catalyst characteristics is presented in Table 4-3.

Table 4-3. Catalyst Characteristics.

Catalyst System	Ford OEM (one catalyst per bank)		Grace EHC	Degussa Main Catalyst
Catalyst Designation	front brick	rear brick	M930037 Cam-E-Lite	OM 6902 Lot 40512
Substrate:				
Material	ceramic		stainless steel foil	ceramic
Cell Density	400 cells/in.^{2}		180 cells/in.^{2}	400 cells/in.^{2}
Precious Metals:				
Precious Metals Types	Pt/Rh	Pt/Rh	Pt/Rh	Pt/Rh
Loading (combined)	60 g/ft.^{3}	28 g/ft.^{3}	80 g/ft.^{3}	70 g/ft.^{3}
Precious Metal Ratio	Pt/Rh = 9/1	Pt/Rh = 5/1	Pt/Rh = 5/1	Pt/Rh = 5/1
Core Length	NA	NA	5.5 in. (front 0.7 in. heated)	6.0 in.
Core Diameter	NA	NA	2.7 in.	5.66 in.
Brick Active Volume	38 in.^{3}	38 in.^{3}	31.5 in.^{3}	151 in.^{3}
Total Active Volume	152 in.^{3}		31.5 in.^{3}	151 in.^{3}

The test vehicle was fitted with an exhaust system modified to accommodate the reformulated main catalyst and EHC. Because of space constraints under the vehicle and the large diameter of the reformulated main catalyst, it was installed much further downstream in the exhaust system than the OEM catalysts. Figure 4-1 shows the OEM and experimental exhaust system configurations. The twin OEM catalysts both reside approximately 355 mm (14 inches) downstream of the exhaust manifold flange. In the experimental exhaust system, blank pipes are installed where the OEM catalysts were, and the EHC/reformulated main catalyst set is installed at the termination of the Y-pipe. This places the face of the reformulated main catalyst approximately 940 mm (37 inches) from the exhaust manifold flange on one side of the exhaust system, and 1.47 mm (58 inches) downstream of the manifold flange on the other side. To compensate for the heat loss, the exhaust system was wrapped with insulated fiber tape from the exhaust manifold flange to the end of the Y-pipe.

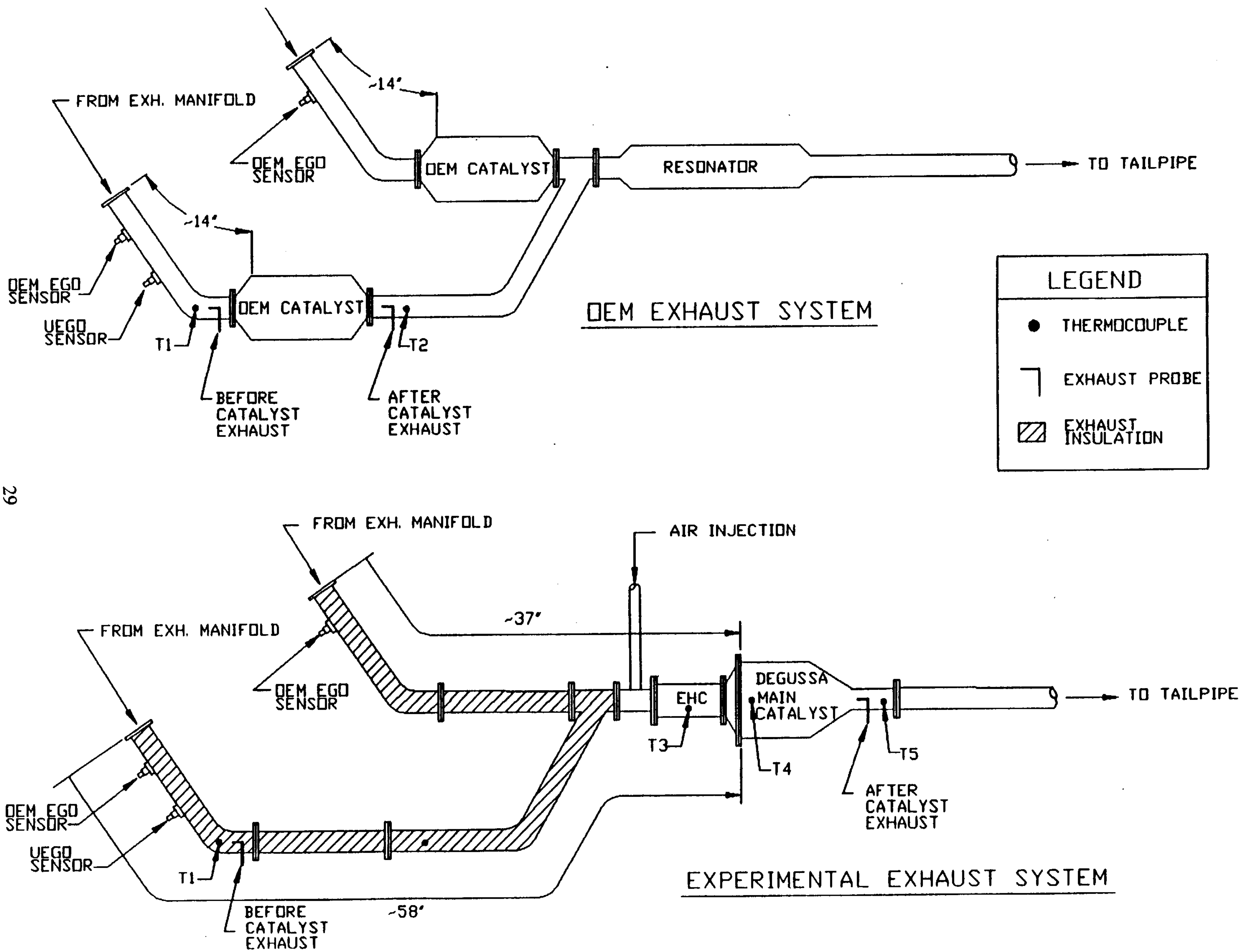

Figure 4-1. Schematic of standard OEM exhaust system and SwRI experimental exhaust system.

Electrically Heated Catalyst Emissions Testing

After work on the exhaust system was completed, the vehicle was prepared for a series of FTP tests to determine the effect of the EHC/reformulated main catalyst system on exhaust emissions. First, the OEM exhaust system was installed on the vehicle to establish a current baseline for exhaust emissions. Then the fuel composition sensor was replaced with a SwRI-generated signal calibrated for E80. The OEM sensor was calibrated for methanol, and would cause over-enrichment during open-loop operation of the vehicle when running on E80. The SwRI circuit was calibrated to provide an appropriate amount of open-loop fuel enrichment for E80. Lastly, the experimental exhaust system was installed incrementally to determine the impact of each component on exhaust emissions. The EHC was operated in a post-crank heating mode. Secondary air was injected for the duration of open-loop operation. A series of three tests were conducted to determine an appropriate air injection flow rate. A summary of the test matrix is given in Table 4-4.

Table 4-4. Emissions Test Matrix.

Test Number	Catalyst	Fuel Sensor Signal	Exhaust Insulation	EHC	EHC Power	Secondary Air injection
E80-OEM-1	OEM	OEM	no	no	none	none
E80-OEM-2	OEM	SwRI	no	no	none	none
E80-CAT-A	Degussa	SwRI	no	no	none	none
E80-CAT-A&INS	Degussa	SwRI	yes	no	none	none
E80-CAT-A&B	Degussa	SwRI	yes	yes	none	none
E80-EHC-7CFM	Degussa	SwRI	yes	yes	Bag 1 - 25 sec Bag 3 - 10 sec	Bag 1 - 115 sec @ 7 cfm Bag 3 - 10 sec @ 7 cfm
E80-EHC-5CFM	Degussa	SwRI	yes	yes	Bag 1 - 25 sec Bag 3 - 10 sec	Bag 1 - 115 sec @ 5 cfm Bag 3 - 10 sec @ 5 cfm
E80-EHC-2CFM	Degussa	SwRI	yes	yes	Bag 1 - 25 sec Bag 3 - 10 sec	Bag 1 - 115 sec @ 2 cfm Bag 3 - 10 sec @ 2 cfm

Results of the exhaust emissions tests conducted to date are given in Table 4-5.

Table 4-5. FTP Exhaust Emissions from FFV Taurus on E80.

Test Number	Est. NMOG[a]	Est. NMOG x RAF[b]	CO	NO_x
E80-OEM-1	0.152	0.102	1.701	0.077
E80-OEM-2	0.147	0.098	1.548	0.130
E80-CAT-A	0.298	0.200	1.825	0.109
E80-CAT-A&INS	0.270	0.181	1.749	0.068
E80-CAT-A&B	0.282	0.189	1.795	0.083
E80-EHC-7CFM	0.077	0.052	0.795	0.068
E80-EHC-5CFM	0.096	0.064	0.744	0.064
E80-EHC-2CFM	0.143	0.096	1.139	0.057

[a] NMOG was estimated using NMHC from the gasoline portion of the fuel as measured by a flame ionization detector (FID) rather than by hydrocarbon speciation.
[b] RAF = 0.67 as measured by Kroll at Volkswagen (SAE 932676)

Comparing the OEM baseline test (E80-OEM-1) with E80-OEM-2, the SwRI-generated fuel sensor signal had a slight positive impact on measured NMOG and CO emissions; however, a slight increase in NO_x emissions was detected. Therefore, it seems likely that the change to the SwRI-generated fuel sensor signal caused the vehicle to operate with less open-loop enrichment than in OEM configuration. A change from the OEM exhaust system to the experimental exhaust system with reformulated main catalyst led to a significant increase in NMOG emissions, as shown by the results of test E80-CAT-A (Table 4-5). A combination of less available thermal energy (due to the placement of the catalyst) and the catalyst formulation likely contributed to the higher emissions results for the reformulated main catalyst as compared to the baseline OEM exhaust emission results. The addition of exhaust insulation in test E80-CAT-A&INS resulted in a reduction of all exhaust emissions. Results from test E80-CAT-A&B show that the addition of the EHC (no heat, no air injection) into the exhaust stream had little effect on exhaust emissions. With the EHC operational in test E80-EHC-7CFM, measured exhaust emissions were reduced significantly from the non-heated configuration (E80-CAT-A&B). Furthermore, emissions were reduced from OEM baseline levels. During this test, secondary air was injected into the exhaust stream ahead of the EHC at a constant flow fare of 7 cfm. Tests were also conducted with 5-cfm and 2-cfm flow rates; however, emissions results from these tests were not as favorable as at 7 cfm.

Detailed results from the baseline test (OEM-1) and the best results with the EHC (E80-EHC-7CFM) are give in Table 4-6. These data show significant reductions in exhaust emissions with the use of the EHC together with a reformulated main catalyst. Estimated NMOG was reduced by nearly 50%, and alcohol emissions were reduced by approximately 65%. However, although aftertreatment technology has demonstrated gains in control of exhaust emissions, further improvements are needed to meet ULEV standards.

Table 4-6. FTP Exhaust Emissions from Ford FFV.

Exhaust Constituents	Baseline Test # E80-OEM-1	EHC Test # E80-EHC-7CFM	Percent Reduction with EHC	ULEV Standards
THC[a] (g/mi)	0.196	0.123	37.2	
CO (g/mi)	1.702	0.796	53.2	1.7
NO_x (g/mi)	0.077	0.068	11.7	0.2
CH_4 (g/mi)	0.044	0.046	-4.5	
NMHC[b] (g/mi)	0.047	0.033	29.8	
Carbonyls[c] (g/mi)	0.014	0.012	14.3	
Alcohols[d] (g/mi)	0.091	0.032	64.8	
Estimated NMOG[e] (g/mi)	0.152	0.077	49.3	
Est NMOG x RAF[f] (g/mi)	0.102	0.052	49.0	0.040
Formaldehyde (mg/mi)	1.49	0.58	61.1	8
Acetaldehyde (mg/mi)	11.19	10.93	2.3	

[a] THC = NMOG + CH4

[b] Gasoline derived NMHC = FIDHC - (CH_4 x FIDRCH4) - (Ethanol x FIDRETH); FIDHC - hydrocarbon measured with flame ionization detector calibrated on propane; FIDRCH4 - FID response factor for methane; FIDRETH - FID response factor for ethanol

[c] Summation of all measured aldehydes and ketones including: formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, isobutyraldehyde + methyl ethyl ketone, and hexanaldehyde

[d] Ethanol only; no methanol was found in exhaust samples

[e] NMOG = NMHC + Carbonyls + Alcohols

[f] RAF = 0.67 as measured by Kroll at Volkswagen (SAE 932676)

Table 4-7 gives individually weighted emissions for each phase of the FTP. These data show that, even with an EHC, nearly 70% of all NMOG emissions are caused by unburned gasoline-derived NMHC and unburned ethanol present during the first 140 seconds of the FTP. These data also show that after 140 seconds, tailpipe exhaust emissions are well controlled, primarily because the catalyst is completely "lit off" and catalyst conversion efficiency is high. Therefore, a method needs to be developed to either bring the complete catalyst to light-off quicker, or momentarily "store" exhaust emissions until the catalyst is completely lit off.

Table 4-7. Weighted FTP Exhaust Emissions - EHC Test # E80-EHC-7CFM.

Exhaust Emission	Individually Weighted Exhaust Emissions (g/mi) Bag 1A (0-140 sec)	Bag 1B (141-505 sec)	Bag 2	Bag	Total Weighted FTP Emissions (g/mi)	Bag 1A Percentage of Total NMOG Emissions
NMHC	0.02	0.01	<0.01	<0.01	0.033	27%
Ethanol	0.03	<0.01	<0.01	<0.01	0.032	42%
Acetaldehyde	0.01	<0.01	<0.01	<0.01	0.011	13%

Future Plans

To further reduce exhaust emissions in the first few minutes of the FTP, SwRI will investigate hydrocarbon adsorber technologies. Degussa has an aftertreatment technology that combines the functions of a hydrocarbon adsorber and a light-off catalyst. This unit would capture the hydrocarbon emissions from the vehicle during cold start while the catalytic material reached light-off temperature. The hydrocarbons would then be desorbed and reduced by the catalytic material in the unit. The main catalyst would continue to provide exhaust emission reductions. In addition, the EHC system may be supplemented with a small hydrocarbon adsorber. This adsorber could be placed ahead of the EHC to trap cranking and start emissions before the EHC is at operating temperature. Therefore, SwRI plans to test both an EHC with reformulated main catalyst supplemented by hydrocarbon adsorber, and a hydrocarbon adsorber/light-off catalyst with reformulated main catalyst during Phase 3.

Task 5 Fuel/Engine/Vehicle System Integration

Objectives

The objective of this task is to manage the overall project, and modify the vehicle as necessary to support engine modifications.

Air Pumps for Air-Assist Atomizers and Electrically Heated Catalyst

The atomizer tests described in Task 3 help to define the size of the air pump that will be required to provide atomizing air flow. Similarly, tests with the aftertreatment systems will determine the size of the air pump required for adding air between the engine and catalyst during the warm-up phase to reduce catalyst warm-up time by supplying excess fuel (relative to engine needs) from the engine controller, and air from the auxiliary air pump.

A Thomas air pump has been obtained from Ford for testing to supply air for the air-assist injectors. The pump was sized for air-assist injectors for a 4-cylinder engine rather than a 6-cylinder like the Taurus 3.0-liter, and the capacity appears to be undersized. However, the Thomas pump will be used to evaluate its performance.

Flexible Fuel Vehicle Fuel Sensor

The fuel sensor in the 1993 Ford Taurus FFV was designed to operate on M85 or gasoline, or any blend or M85 and gasoline. It was not designed to operate on ethanol or ethanol/gasoline fuel blends; however, it responds for ethanol fuels roughly correctly for the desired open-loop fueling needed.

Ford supplied confidential information for the fuel sensor response expected for both ethanol/gasoline blends and methanol/gasoline blends. Based on the supplied data, the sensor response for E80 should result in the engine controller (EEC-IV) supplying too much E80 fuel during open-loop operation of the vehicle. Therefore, tests were performed where the fuel sensor signal was replaced with a constant frequency signal to more accurately meter the E80 fuel during open-loop operation. During closed-loop operation on the exhaust oxygen sensor, the error in open-loop operation should not have an impact on engine emissions. Emissions tests described under Task 4 showed little improvement when the fuel signal was corrected, although the change was in the direction expected with slightly lower carbon monoxide and slightly higher nitric oxides. These tests appeared to demonstrate that the adaptive learning algorithms in the OEM Ford Taurus FFV were quite adept at correcting for the error in the signal from the fuel sensor based on closed-loop feedback from the EGO sensor in the exhaust.

Task 6 Integrated Fuel/Engine System Optimization

Objective

The objective of this task was to develop a SwRI RPECS (Rapid Prototyping Engine Control System) engine controller for complete control of all engine functions. This is not a device that modifies signals being sent to the OEM engine controller; rather it completely replaces that controller. This is a shared task between Task 3 and Task 6 of this project.

Rapid Prototyping Engine Control System Engine Controller Hardware

The hardware for the RPECS engine controller was constructed as planned in described by Bourn et al. (1994). This is basically a PC-based engine controller that uses the PC for higher-level logic development that is programmed in C-code, and for input and output from the engine controller. However, many lower-level, engine specific tasks are off-loaded to a Silicon Systems 67F687 engine controller chip.

The engine test cell version of this controller is shown in Figure 6-1. The key to this setup is the real-time operating system extensions together with the custom boards. The custom boards off-load the most time-critical engine control operations, such as injector and ignition timing. Because of this reduction in the PC's timing requirements, all control codes may be written in the high-level language C. In this way, new control strategies may be very efficiently and quickly implemented and tested.

Rapid Prototyping Engine Control System Engine Controller Software

Software development for the PC-based, engine-test cell custom engine controller sufficient to run the engine was completed. The initial features set in the controller include:

* Open-loop fueling computed using either a mass airflow sensor or speed-density. A combination of mass air flow (MAF) or speed-density may also be used, with the method chosen based on current engine operating conditions.

* Closed-loop fueling with wide-range UEGO feedback.

* Cylinder-event based control during start-up. Allows for cylinder event by cylinder event based control of fueling and spark timing.

* Air-assist or OEM injector control.

As features are added to the software, they are being tested on the hardware in the Controls Laboratory, using a 68HC11 EVB2 board to simulate the crank/cam pulses from the engine, and using power resistors/LEDs to simulate the injectors, ignition coils, idle-air control and EGR valves.

Model-based control will be developed and implemented into the engine controller in the future. This approach uses mean-value models for both air flow and fuel flow into the engine.

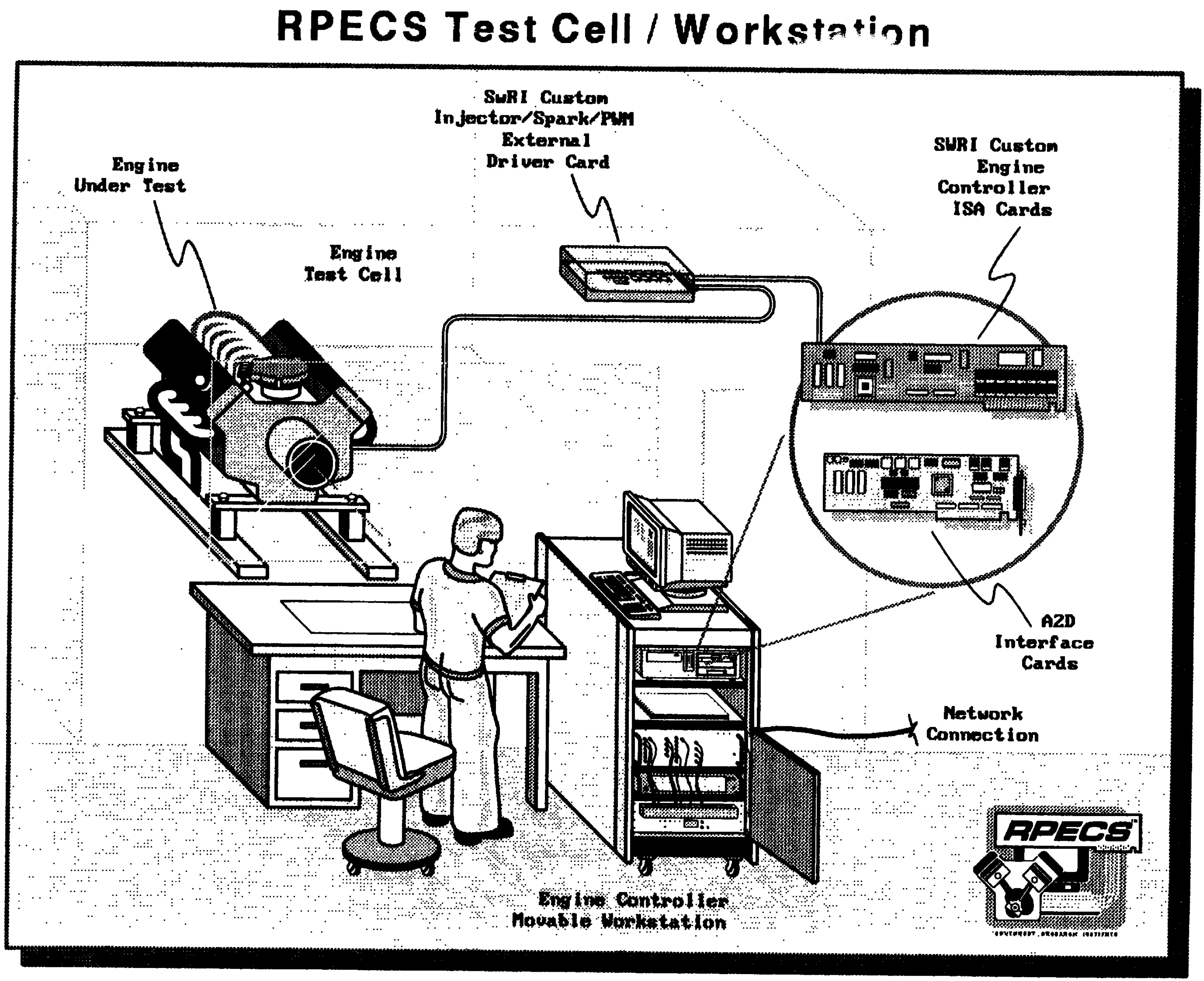

Figure 6-1. The PC-based controller for engine test cell.

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Appendix A

Standard Specification for Fuel Ethanol (Ed85-Ed75) for Automotive Spark-Ignition Engines (Draft ASTM Standard)

D-2 D XXXX (Draft of 2/28/95)

Standard Specification for Fuel Ethanol (Ed85-Ed75) for Automotive Spark-Ingition Engines[1]

1. Scope

1.1 This specification covers a fuel blend, nominally 85 to 75 volume % denatured fuel ethanol and 15 to 25 additional volume % hydrocarbons for use in ground vehicles with automotive spark-ignition engines. Appendix XI discusses the significance of the properties specified.

1.2 The values stated in SI units are to be regarded as the standard. Values given in parentheses are provided for information only.

1.3 The following precautionary caveat pertains only to the test method portion, Annex A1 of this proposed specification.
This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents[2]

2.1 ASTM Standards:
- D 86 Test Method for Distillation of Petroleum Products[3]
- D 130 Test Method for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish test[3]
- D 381 Test Method for Existent Gum in Fuels by Jet Evaporation[3]
- D 512 Test Methods for Chloride Ion in Water[4]
- D 525 Test Method for Oxidation of Gasoline (Induction Period Method)[3]
- D 1193 Specification for Reagent Water[4]
- D 1266 Test Method for Sulfur in Petroleum Products (Lamp Method)[3]
- D 1613 Test Method for Acidity in Volatile Solvents and Chemical Intermediates Used in Paint, Varnish, Lacquer, and Related Products[5]
- D 1688 Test Method for Copper in Water[4]
- D 2622 Test Method for Sulfur in Petroleum Products by X-Ray Spectrometry Method[6]
- D 2988 Test Method for Water-Soluble Halide Ion in Halogenated Organic Solvents and Their Admixtures[7]
- D 3120 Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry[6]
- D 3231 Test Method for Phosphorus in Gasoline[6]
- D 3545 Test Method for Alcohol Content and Purity of Acetate Esters by Gas Chromatography[5]
- D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products[8]
- D 4177 Method for Automatic Sampling of Petroleum and Petroleum Products[8]

D 4307 Practice for Preparation of Liquid Blends for Use as Analytical Standards[6]
D 4626 Practice for Calculation of Gas Chromatographic Response Factors[6]
D 4806 Specification for Denatured Fuel Ethanol for Blending with Gasolines for use as Automotive Spark-Ignition Engine Fuel[6]
D 4814 Specification for Automotive Spark-Ignition Engine Fuel[6]
D 4815 Test Method for Determination of MTBE, ETBE, TAME, DIPE, tertiary-Amyl Alcohol and C1 to C4 Alcohols in Gasoline by Gas Chromatography[6]
D 4929 Test Methods for Determination of Organic Chloride Content in Crude Oil[6]
D 4953 Test Method for Vapor Pressure of Gasoline and Gasoline-Oxygenate Blends (Dry Method)[6]
D 5059 Test Method for Lead in Gasoline by X-ray Spectroscopy[6]
D 5190 Test Method for Vapor Pressure of Petroleum Products (Automatic Method)[6]
D 5191 Test Method for Vapor Pressure of Petroleum Products (Mini Method)[6]
D 5453 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Motor Fuels and Oils by Ultraviolet Fluorescence[6]
D 5501 Test Method for the Determination of Ethanol Content of Denatured Fuel Ethanol by Gas Chromatography[6]
E 203 Test Method for Water Using Karl Fischer Reagent[7]

3. Terminology

3.1 Definitions:
3.1.1 ethanol, n -ethyl alcohol, the chemical compound C_2H_5OH.
3.1.2 methanol, n -methyl alcohol, the chemical compound CH_3OH.
3.2 Description of Terms Specific to this Standard:
3.2.1 denaturants,- gasoline, toxic or noxious materials added to ethanol to make it unsuitable for beverage use and suitable for automotive fuel use.
3.2.2 denatured fuel ethanol,-fuel ethanol made unfit for beverage use by the addition of toxic or noxious materials.
3.2.3 fuel ethanol,-ethanol with impurities common to its production (including water but excluding denaturants).
3.2.4 fuel ethanol (Ed85-Ed75),-blend of ethanol and hydrocarbon of which the ethanol portion is nominally 85 to 75 volume % denatured fuel ethanol.
3.2.5 higher alcohols,-aliphatic alcohols of general formula C(N)H(2N+1)OH with N being 3 to 8.
3.2.6 hydrocarbon,-those components in an ethanol-hydrocarbon blend containing only hydrogen and carbon

4. Fuel Ethanol (Ed85-Ed75) Performance Requirements

4.1 Fuel Ethanol (Ed85-Ed75) shall conform to the following requirements:

Ethanol plus higher alcohols minimum volume % (see 4.1.1 for Volatility Class Criteria)	Class 1 79 Class 2 74 Class 3 70
Methanol maximum, volume %	0.5
Higher aliphatic alcohols (C3-C8), Max,Vol%	2
Hydrocarbon (including denaturant)/aliphatic ether blends containing up to 2.7 weight oxygen, volume %	Class 1 -21 Class 2 -26 Class 3 17-30
Water maximum, mass %	1.0
Vapor pressure, kPa (psi) Class 1 Class 2 Class 3	 38-59 (5.5-8.5) 48-65 (7.0-9.5) 66-83 (9.5-12.0)
Acidity as acetic acid maximum, mg/kg	50
Gum Content, Solvent Washed, maximum, mg/100 mL	5
Gum Content, Unwashed, maximum, mg/100 mL	20
Total Chlorine as Chlorides maximum, mg/kg	2
Inorganic Chloride maximum, mg/kg	1
Lead maximum, mg/litre	Class 1 2.6 Class 2 2.6 Class 3 3.9
Phosphorus maximum, mg/litre	Class 1 0.3 Class 2 0.3 Class 3 0.4
Copper, maximum, mg/litre	0.07
Sulfur maximum, mg/kg	Class 1 210 Class 2 260 Class 3 300
Appearance	The product shall be visibly free of suspended or precipitated contaminants (clear and

bright). This shall be determined at ambient temperature or 21 Deg. C (70 Deg. F), whichever is higher.

NOTE 1- Most of the requirements cited are based on the best technical information currently available. Requirements for sulfur, phosphorus, and lead are based on the use of gasoline defined in Specification D 4814 and the understanding that control of these elements will affect catalyst lifetime. The lead maximum is limited for Class 1 and Class 2 fuels to the lower limit of the test method. As greater experience is gained from field use of E85 vehicles and further vehicle hardware developments for the use of ethanol content fuels occurs, it is expected that many of these requirements will change.

4.1.1 Vapor pressure is varied for seasonal and climatic changes by providing three vapor pressure classes for fuel ethanol (Ed85-Ed75). The seasonal and geographical distribution for three vapor pressure classes is shown in Table 1. Class 1 encompasses geographical areas with 6 hr 10th percentile minimum ambient temperature of greater than 5 Deg. C (41 Deg. F). Class 2 encompasses geographical areas with 6 hr 10th percentile minimum ambient temperature of greater than -5 Deg. C (23 Deg. F) but less than +5 Deg C (41 Deg. F). Class 3 encompasses geographical areas with 6 hr 10th percentile minimum ambient temperature less than or equal to -5 Deg. C (23 Deg. F).

4.1.2 The hydrocarbons blended with the denatured fuel ethanol shall have a maximum boiling point of 225 Deg. C (437 Deg. F) by Test Method D 86, oxidation stability of 240 min minimum by Test Method D 525, and No. 1 maximum copper strip corrosion by Test Method D 130. The hydrocarbons may contain aliphatic ethers as blending components as are customarily used for automotive spark-ignition engine fuel.

4.1.3 The denaturant for the denatured fuel ethanol used in making Fuel Ethanol (Ed85-Ed75) shall meet the requirements of ASTM D 4806 Section 5.0.

4.1.4 Use of unprotected aluminum in fuel Ethanol (Ed85-Ed75) distribution and dispensing equipment will introduce insoluble aluminum compounds into the fuel, causing plugged vehicle fuel filters. Furthermore, this effect can be exaggerated even with protected aluminum by elevated fuel conductivity caused by contact with nitrile rubber dispensing hose. Therefore, unprotected aluminum and unlined nitrile rubber dispensing hose should be avoided in fuel ethanol (Ed85-Ed75) fuel distribution and dispensing systems[9].

5. Sampling

5.1 Sample in accordance with Practice D 4057, except that water displacement (10.3.1.8 of Practice D 4057) shall not be used.

5.2 Where practical, fuel ethanol (Ed85-Ed75) should be sampled in glass containers. If samples must be collected in metal containers, do not use soldered containers. This is because the soldering flux residues in the containers and lead in the solder can contaminate the sample. Plastic containers should be avoided.

5.3 A minimum sample size of about 1 L (1 U.S. qt) is recommended.

6. Test Methods

6.1 Determine the requirements enumerated in this specification in accordance with the following test methods:

Note 2. The appropriateness of ASTM test methods cited has not been demonstrated for use with fuel ethanol (Ed85-Ed75). In addition, the test method outlined in the Annex A1 is in the developmental stage and lacks precision and bias determinations.

6.1.1 Ethanol- Test Method D 5501

6.1.2 Hydrocarbon/aliphatic ether blend content- Use Test method D5501 to determine other alcohols, methyl tertiary-butyl ether (MTBE), and other ethers. Determine water by the Karl Fischer test method (see 6.1.10). Subtract the concentration of alcohols and water from 100 to get the percent hydrocarbon/aliphatic ether.

6.1.3 Vapor Pressure - Test Method D 4953, D 5190, or D 5191.

6.1.4 Acidity- Test Method D 1613.

6.1.5 Gum Content, solvent washed and unwashed- Test Method D 381.

6.1.6 Total Chlorine as Chloride- Test Method D 4929, Method B.

6.1.7 Inorganic Chloride- Test Methods D 512 or D 2988. An alternate method for inorganic chloride is found in Annex A1.

6.1.8 Lead- Test Method D 5059. With Test Method D 5059, prepare the calibration standards using ethanol (reagent grade) as the solvent to prevent errors caused by large differences in carbon-hydrogen ratios.

6.1.9 Phosphorus- Test Method D 3231.

6.1.10 Water- Test Method E 203.

6.1.11 Copper- Modification of Test Method D 1688 as outlined in D 4806.

6.1.12 Sulfur- Test Methods D 1266, D 2622, D 3120, or D5453. With Test Method D 2622, prepare the calibration standards using ethanol (reagent grade) as the solvent to prevent errors caused by large differences in carbon-hydrogen ratios.

7. Keywords

7.1 acidity; alcohol; automotive spark-ignition engine fuel; chloride; copper corrosion; ether; gum content, solvent washed; fuel ethanol (Ed85-Ed75) for automotive spark-ignition engines; hydrocarbon; inorganic chloride; lead; MTBE; oxidation stability; oxygenates; phosphorus; sulfur; total chlorine; vapor pressure; volatility; water.

Footnotes.

(1) This specification is under the jurisdiction of Committee D-2 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.A on Gasoline and Oxygenated Fuels.

(2) Reference to the following documents is to be the latest issue unless otherwise specified.

(3) Annual Book of ASTM Standards, Vol 05.01.

(4) Annual Book of ASTM Standards, Vol 11.01.

(5) Annual Book of ASTM Standards, Vol 06.03.

(6) Annual Book of ASTM Standards, Vol 05.02.

(7) Annual Book of ASTM Standards, Vol 15.05.

(8) Annual Book of ASTM Standards, Vol 05.03.

(9) American Automobile Manufacturers Association, "Fuel Methanol Compatibility Standards and Dispensing Equipment List for M85 Fueled Vehicles", October, 1994.

Doc# DRAFT 11

Table 1 Seasonal and Geographical Volatility Specifications for Fuel Ethanol (Ed85-Ed75)

This schedule subject to agreement between purchaser and seller, denotes the vapor pressure class of the fuel at the time and place of bulk delivery to fuel dispensing facilities for the end user. Shipments should anticipate this schedule

State	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Alabama	2	2	2	2	2/1	1	1	1	1	1/2	2	2
Alaska												
Southern Region	3	3	3	3	3/2	2/1	1	1/2	2/3	3	3	3
South Mainland	3	3	3	3	3/2	2/1	1/2	2	2/3	3	3	3
Arizona												
N of 34 deg Latitude	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
S of 34 deg Latitude	2	2	2	2/1	1	1	1	1	1	1/2	2	2
Arkansas	3	3	3/2	2/1	1	1	1	1	1/2	2	2/3	3
California (1)												
North Coast	2	2	2	2	2	2/1	1	1	1	1/2	2	2
South Coast	3/2	2	2	2	2/1	1	1	1	1	1/2	2/3	3
Southeast	3	3/2	2	2	2/1	1	1	1	1/2	2	2/3	3
Interior	2	2	2	2	2	2/1	1	1	1	1/2	2	2
Colorado												
E of 105 deg Longitude	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
W of 105 deg Longitude	3	3	3	3	3/2	2	2/1	1/2	2/3	3	3	3
Connecticut	3	3	3	3/2	2	2/1	1	1	1/2	2	2/3	3
Delaware	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
District of Columbia	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
Florida												
N of 29 deg Latitude	2	2	2	2/1	1	1	1	1	1	1/2	2	2
S of 29 deg Latitude	2	2/1	1	1	1	1	1	1	1	1	1/2	2
Georgia	3	3/2	2	2/1	1	1	1	1	1	1/2	2	2/3
Hawaii	1	1	1	1	1	1	1	1	1	1	1	1
Idaho	3	3	3	3/2	2	2	2/1	1/2	2	2/3	3	3
Illinois												
N of 40 deg Latitude	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
S of 40 Deg Latitude	3	3	3	3/2	2/1	1	1	1	1/2	2/3	3	3
Indiana	3	3	3	3/2	2/1	1	1	1	1/2	2/3	3	3
Iowa	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
Kansas	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
Kentucky	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
Louisiana	2	2	2	2/1	1	1	1	1	1	1/2	2	2
Maine	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Maryland	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
Massachusetts	3	3	3	3/2	2	2/1	1	1	1/2	2	2/3	3
Michigan												
Lower Michigan	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Upper Michigan	3	3	3	3	3/2	2/1	1	1/2	2	2/3	3	3
Minnesota	3	3	3	3	3/2	2/1	1	1/2	2	2/3	3	3
Mississippi	2	2	2	2/1	1	1	1	1	1	1/2	2	2
Missouri	3	3	3	3/2	2/1	1	1	1	1/2	2/3	3	3
Montana	3	3	3	3	3/2	2	2/1	1/2	2/3	3	3	3
Nebraska	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Nevada												
N of 38 deg Latitude	3	3	3	3/2	2	2	2/1	1/2	2	2/3	3	3
S of 38 deg Latitude	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
New Hampshire	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3

New Jersey	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
New Mexico												
N of 34 deg Latitude	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
S of 34 deg Latitude	3	3	3/2	2/1	1	1	1	1	1	1/2	2/3	3
New York												
N of 42 deg Latitude	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
S of 42 deg Latitude	3	3	3	3/2	2/1	1	1	1	1/2	2	2/3	3
North Carolina	3	3	3/2	2	2/1	1	1	1	1/2	2/3	3	3
North Dakota	3	3	3	3	3/2	2/1	1	1/2	2	2/3	3	3
Ohio	3	3	3	3/2	2/1	1	1	1	1/2	2/3	3	3
Oklahoma	3	3	3	3/2	2/1	1	1	1	1/2	2	2/3	3
Oregon												
E of 122 deg Longitude	3	3	3	3/2	2	2	2/1	1/2	2	2/3	3	3
W of 122 deg Longitude	3	3/2	2	2	2	2/1	1	1	1/2	2	2	2/3
Pennsylvania												
N of 41 deg Latitude	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
S of 41 deg Latitude	3	3	3	3/2	2	2/1	1	1	1/2	2	2/3	3
Rhode Island	3	3	3	3/2	2/1	1	1	1	1/2	2	2/3	3
South Carolina	2	2	2	2/1	1	1	1	1	1	1/2	2	2
South Dakota	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Tennessee	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
Texas												
N of 31 deg Latitude	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
S of 31 deg Latitude	2	2	2	2/1	1	1	1	1	1	1/2	2	2
Utah	3	3	3	3/2	2	2/1	1	1	1/2	2/3	3	3
Vermont	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Virginia	3	3	3/2	2	2/1	1	1	1	1/2	2	2/3	3
Washington												
E of 122 deg Longitude	3	3	3/2	2	2	2/1	1	1	1/2	2/3	3	3
W of 122 deg Longitude	3	3/2	2	2	2	2/1	1	1	1/2	2	2	2/3
West Virginia	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Wisconsin	3	3	3	3/2	2	2/1	1	1/2	2	2/3	3	3
Wyoming	3	3	3	3	3/2	2	2/1	1/2	2	2/3	3	3

Details of State Climatological Division by county as indicated

California North Coast—Alameda Contra Costa Del Norte Humboldt Lake Marin Mendocino Monterey Napa San Benito San Franci San Mateo Santa Clara Santa Cruz Solano Sonoma Trinity

California Interior—Lassen Modoc Plumas Sierra Siskiyou Alpine Amador Butte Calaveras Colusa El Dorado Fresno Glenn Kern (exc that portion lying east of the Los Angeles County Aqueduct) Kings Madera Mariposa Merced Placer Sacramento San Joac Shasta Stanislaus Sutter Tehama Tulare Tuolumne Yolo Yuba Nevada

California South Coast—Orange San Diego San Luis Obispo Santa Barbara Ventura Los Angeles (except that portion north of the Gabriel Mountain range and east of the Los Angeles County Aqueduct)

California Southeast—Imperial Riverside San Bernardino Los Angeles (that portion north of the San Gabriel Mountain range and east of Los Angeles County Aqueduct) Mono Inyo Kern (that portion lying east of the Los Angeles County Aqueduct)

ANNEXES

(Mandatory Information)

A1. TEST METHOD FOR DETERMINATION OF INORGANIC CHLORIDE IN FUEL ETHANOL (Ed85-Ed75)

A1.1 Scope

A1.1.1 This test method covers a procedure to determine the inorganic chloride in fuel ethanol (Ed85-Ed75) in the range of concentrations 0.4 to 2.0 ppm.

A1.1.2 The values stated in SI units are to be regarded as the standard.

A1.2 Summary of Test Method.

A1.2.1 The sample is concentrated, acidified, and treated with silver nitrate. The turbidity is visually compared with standards.

A1.3 Significance and Use

A1.3.1 Because of the corrosive nature of inorganic chloride to the fuel system of internal combustion engines, a means to measure low levels of inorganic chloride in fuel ethanol (Ed85-Ed75) is required.

A1.4 Apparatus

A1.4.1 Distillation Apparatus-500mL distillation flask, condenser and 250 mL graduated cylinder as collector.

A1.4.2 Nessler Tubes, 100 mL, matched, tall form.

A1.5 Reagents and Materials

A1.5.1 Nitric Acid (HNO_3) Solution, 1 part 15.7M to 1 part demineralized water. (Warning-See Note A1.1.)

Note-A1.1: **Warning-Corrosive. Health hazard.**

A1.5.2 Silver Nitrate Solution, 0.1 M. (Warning -See Note A1.2.)

Note-A1.2: **Warning Health Hazard.**

A1.5.3 Ethanol, halide- and sulfide-free by distillation. (Warning-See Note A1.3.)

Note-A1.3: Warning-Flammable. Health hazard.

A1.5.4 Demineralized Water, halide- and sulfide-free.

A1.5.5 Sodium Chloride (NaCl)

A1.6 Standards

A1.6.1 Dissolve 0.845 g of dry sodium chloride (NaCl) in halide- and sulfide-free water and dilute to 1 L in a volumetric flask. Mix thoroughly and label Solution A (0.5 mg Cl/mL).

A1.6.2 Pipet 10 mL of solution A into a 1 L volumetric flask. Dilute to volume with halide- and sulfide-free water. Mix thoroughly and label Solution B (0.005 mg Cl/mL).

A1.6.3 In matching Nessler tubes, prepare the following standards:

	Blank	1	2	3	4	5
Solution B, mL (pipet)	0.0	1.0	2.0	3.0	4.0	5.0
Ethanol, mL (Cl-free)	80	80	80	80	80	80

A1.6.4 For each standard follow A1.7.4 to A1.7.8.

A1.6.5 The turbidity standards are affected by light and are not stable. Prepare fresh standards (from solution B) for each group of samples.

A1.7 Procedure

A1.7.1 Clean all glassware with 1 M HNO_3, and rinse with demineralized water and halide- and sulfide-free ethanol.

A1.7.2 Measure 320 mL of sample in a graduated cylinder and put into the distillation flask, add boiling beads. Distill the sample into a graduated cylinder until 240 mL of the distillate is obtained. Use 4 mL of the concentrated residue from the distillation flask as follows.

A1.7.3 Add a 4 mL sample to a 100 mL Nessler tube.

A1.7.4 Add 80 mL of halide- and sulfide-free ethanol to the sample in the Nessler tube.

A1.7.5 Dilute the contents of all tubes (sample and standards) to the 100 mL mark with halide- and sulfide-free water.

A1.7.6 Pipet 2 mL of nitric acid solution (1 part 15.7 M acid to 1 part demineralized water) into each tube.

A1.7.7 Pipet 1 mL of 0.1 M silver nitrate solution into each tube.

A1.7.8 Stopper and mix thoroughly by inverting.

A1.7.9 Allow the tubes to stand in the dark for 5 min. Visually compare the sample to the standard solutions while looking vertically against a black background. Record the millilitres of standard Solution B that match the sample.

A1.8 Calculation

(A1.1) Calculate the results as follows:

$$(A)(B)(0.001)(1000000)/(320/80)(4)(0.789) = \text{ppm Cl}$$

where:

A =mL of Solution B that matched sample,
B =mg Cl/mL of Solution B,
0.001 =mg to g,
320/80 =concentration factor,
4 = mL of sample, and
0.789 = relative density of ethanol at 20 deg C (68 Deg F) compared to water at 4 deg C (39 Deg F)

A1.9 Precision and Bias

A1.9.1 Precision- The precision of this test method for measuring inorganic chloride in fuel ethanol (Ed85-Ed75) is being determined.

A1.9.2 Bias- Since there is no accepted reference material for determining bias for the procedure in this test method for measuring inorganic chloride in fuel ethanol (Ed85-Ed75), bias has not been determined.

APPENDICES

(Nonmandatory Information)

XI. SIGNIFICANCE OF SPECIFICATION FOR FUEL ETHANOL (Ed85-Ed75) FOR AUTOMOTIVE SPARK-IGNITION ENGINES.

X1.1 Ethanol

X1.1.1 The ethanol content of fuel ethanol (Ed85-Ed75) is a critical parameter as it affects the capability of the fuel metering system of the dedicated Ed85-Ed75 vehicle to establish the proper air/fuel ratio for optimum vehicle operation. This is much less of a concern for multifuel -capable vehicles than for dedicated Ed85-Ed75 vehicles. Ethanol content may also affect the lubricating properties of the fuel, the water tolerance of the fuel and the ability to meet cold and cool area volatility requirements.

X1.1.2 The inclusion of impurities, some denaturants, and contaminants, except for the deliberately added hydrocarbons or additives or both, can impact adversely on the properties and performance of fuel ethanol (Ed85-Ed75) as an automotive spark-ignition engine fuel. The quantities of some of these materials are controlled by specified property limits. The limits on water, higher molecular weight alcohols, and methanol, and types of denaturants as well as minimums on the amount of ethanol and hydrocarbons limit, but do not prevent,the presence of trace materials.

X1.2 Hydrocarbon

X1.2.1 Hydrocarbons are deliberately added to provide improved cold startability and warm up driveability. The addition of hydrocarbon to fuel ethanol changes its volatility and can affect the flammability of fuel tank vapors.

X1.2.2 This specification does not control the composition of the hydrocarbons added to the denatured fuel ethanol. However the hydrocarbons shall be stable, noncorrosive, and be in the boiling range of automotive spark-ignition engine fuel as specified in D 4814. . .

X1.3 Vapor Pressure

X1.3.1 The addition of volatile hydrocarbons is required for adequate cold startability. The addition of hydrocarbons which are too volatile can contribute to hot fuel handling problems. Higher vapor pressures are required at colder ambient temperatures while lower volatility fuels are less prone to hot fuel handling problems at higher (summertime) ambient temperatures. Excessive vapor pressure contributes to evaporative emissions. Lower and upper limits on vapor pressure for the three volatility classes are used to define the acceptable range of volatile components to ensure adequate vehicle performance.

X1.4 Acidity

X1.4.1 Very dilute aqueous solutions of organic acids such as acetic acid are highly corrosive to a wide range of metals and alloys. It is therefore necessary to keep such acids at a very low level.

X1.5 Gum Content, Solvent Washed and Unwashed

X1.5.1 The test for gum content, solvent washed, measures the amount of residue after the evaporation of the fuel and following a heptane wash. The heptane wash removes the heptane-soluble, nonvolatile material such as additives, carrier oils used with the additives, and diesel fuel. Gum content, unwashed, consists of fuel-insoluble and fuel soluble gum. The fuel-insoluble portion can clog fuel filters. Both can be deposited on surfaces when the fuel evaporates.

X1.5.2 Gum content, solvent washed, can contribute to deposits on the surface of carburetors, fuel injectors, and intake manifolds, ports, valves and valve guides. The impact of gum content, solvent washed, on malfunctions of modern engines which can operate on fuel ethanol (Ed85-Ed75) has not been fully established but is based on limited experienced gained with M85-M70 fuels in field tests and from historic gasoline limits. Performance effects depend on where the deposits form, the presence of other deposit precursors such as airborne debris, blowby and exhaust gas recirculation gases, oxidized engine oil, and the amount of deposit.

X1.5.3 The difference between the gum content, unwashed, and gum content, solvent washed, values can be used to assess the presence and amount of nonvolatile material in the fuel. Additional analytical testing is required to determine if the material is additive, carrier oil, diesel fuel, etc.

X1.5.4 The gum content, unwashed, limit is intended to limit high-boiling contaminants, like diesel fuel, that can affect engine performance, yet allow the use of appropriate levels of deposit control additives with carrier oils in fuel ethanol (Ed85-Ed75).

X1.5.5 Because the precision statements for D 381 were developed using only data on hydrocarbons, they may not be applicable to fuel ethanol (Ed85-Ed75).

X1.6 Total Chlorine

X1.6.1 Ionic (inorganic) and organic chlorine are corrosive to many metals, and it is desirable to minimize organic and ionic chlorine compounds in fuel ethanol (Ed85-Ed75).

X1.6.2 A total chlorine limit of 2 mg/kg, maximum has been found to be inadequate in protecting some fuel system components. An inorganic chloride limit of 1 mg/kg , maximum, is specified to provide additional protection.

X1.7 Lead

X1.7.1 Most vehicles equipped to operate on fuel ethanol (Ed85-Ed75) are equipped with exhaust catalysts that control emissions of aldehydes (formaldehyde and acetaldehyde) as well as regulated emissions. Lead compounds deactivate the catalyst and are therefore limited to trace amounts.

X1.8 Phosphorus

X1.8.1 Like lead, phosphorus deactivates exhaust catalysts and is limited to trace amounts.

X1.9 Appearance

X1.9.1 Turbidity, phase separation, or evidence of precipitation normally indicates contamination.

X1.10 Water

X1.10.1 The solubility of hydrocarbon in fuel ethanol (Ed85-Ed75) and blends with gasoline as may occur in multi-fuel capable vehicles decreases with lowering temperature and increasing water content. Separation of the hydrocarbon from the fuel will adversely affect cold starting and driveability and denaturing. Water may affect the calibration of some types of composition sensors of multi-fuel capable vehicles. Water also reduces the energy content of the fuel and thus adversely affects fuel economy and power. Because some degree of water contamination is practically unavoidable in transport and handling, and because the fuel ethanol (Ed85-Ed75) is miscible with water, the water content of fuel ethanol (Ed85-Ed75) is limited to reduce the potential for problems.

X1.11 Copper

X1.11.1 Copper is a very active catalyst for low-temperature oxidation of hydrocarbons. Experimental work has shown that copper concentrations higher than 0.012 mg/kg in commercial gasolines may significantly increase the rate of gum formation.

X1.12 Sulfur

X1.12.1 The limit on sulfur content is included to protect against engine wear, deterioration of engine oil, corrosion of exhaust system parts, and exhaust catalyst deactivation.

jmd 2/28/95

Doc# DRAFT 8

Appendix B

SAE J1832 - SAE Recommended Practice for Gasoline Fuel Injector

FUEL INJECTION PUMPS—HIGH PRESSURE PIPES (TUBING) FOR TESTING—SAE J1418 DEC87

SAE Standard

Report of the Engine Committee approved December 1987. This report references ISO 4093.

1. Purpose—This standard specifies the dimensional requirement of a range of high pressure pipes for use in the bench testing and setting of fuel injection pumps.

Only dimensions and requirements affecting the hydraulic characteristic of the pipes are defined. Other requirements, such as the type of end connections and shape of the pipes when bent, are not included. These depend on the connections provided at pump outlets and injector inlets, and on the design features of individual pumps and test benches.

2. Description—The range of pipes specified enables pump and engine manufacturers to choose suitable pipe sizes for pump deliveries up to 300 mm^3 per stroke per cylinder. The particular pipe to be used shall be identified by the pump manufacturer in the test specification for each individual pump type and application.

3. Dimension—The seven standardized sizes of pipes are shown in Table 1. Dimensions are in millimeters.

4. General Requirements

4.1 The pipes may be of ferrous material, usually cold-drawn mild steel, conforming to SAE J529 MAR85.

4.2 After end connections are made, any closing-in or reduction in opening of the pipe shall be removed to a depth of at least twice the length of the deformed end of the pipe. Any closing-in of the ends after extended use shall also be eliminated.

TABLE 1

Item #	Internal Diameter	External Diameter min	Length	Minimum Central Line Bend Radius*
1	2.0 ± 0.025	6	600 ± 5	16
2	2.0 ± 0.025	6	845 ± 5	16
3	3.0 ± 0.025	6	600 ± 5	25
4	3.0 ± 0.025	6	1000 ± 5	25
5	3.0 ± 0.025	6	750 ± 5	25
6	1.6 ± 0.025	6	600 ± 5	16
7	2.0 ± 0.025	6	450 ± 5	16

*Bends may affect the pump fuel delivery. Pipes should be straight and uniform with as large as possible bending radii.

4.3 Pipes shall be cleaned internally after the ends are made and bent in order to remove extraneous matter.

4.4 During storage, the pipes should be protected internally against corrosion and contamination.

4.5 Flow specifications for straight lines are not applicable to bent lines; therefore, straight-line flow specifications are not provided.

GASOLINE FUEL INJECTOR—SAE J1832 NOV89

SAE Recommended Practice

Report of the Fuel Injection Subcommittee approved November 1989. Rationale statement available.

1. Scope—This SAE Recommended Practice promotes uniformity in the evaluation and qualification tests conducted on fuel injectors used in gasoline engine applications. Its scope is limited to electronically actuated fuel injection devices used in automotive port or throttle body fuel injection systems where fuel supply pressure is below 500 kPa. It is further restricted to bench type tests. More specifically this document is intended for use as a guide to the following:

1.1 Identify and define those parameters that are used to measure fuel injector characteristics or performance. The parameters included in this document are listed along with their recommended symbol where appropriate:

Closing Time (CT)
Coil Inductance (L)
Coil Resistance (R)
Dynamic Flow (Q_d)
Dynamic Flow Calculated (Q_{dc})
Dynamic Flow Rate (Q)
Dynamic Minimum Operating Voltage (DMOV)
Dynamic Set Point (PW_{sp})
Dynamic Set Point Flow (Q_{sp})
External Leakage
Flow-Offset (Y)
Insulation Resistance (IR)
Linear Flow Range (LFR)
Linearity Deviation (LD)
Maximum Overload Voltage
Opening Time (OT)
Operating Voltage Range
Period (P)
Pulse Width (PW)
Pressure Drop Ratio (PDR)
Repeatability
Slope (m)
Slope Approximated (m_a)
Spray Pattern
Stability (S)
Static Drop-Out Current (I/S-OFF)
Static Flow Rate (Qs)
Static Minimum Operating Voltage (SMOV)
Static Pull-In Current (I/S-ON)
Time-Offset (X)
Working Flow Range (WFR)

1.2 Establish test procedures, and recommend test equipment and methods to measure and quantify these parameters.

1.3 Standardize use of nomenclature specifically related to fuel injectors.

2. Injector Types

2.1 Fuel Flow Path—Injectors may be classified as top or bottom feed based on the fuel path. Fuel enters at the top of a "top feed" injector (Fig. 1a) and near the bottom or side of the "bottom feed" (Fig. 1b) injector. Metered fuel exits through the bottom in both type injectors.

A fuel filter is typically designed as an integral part of the injector at the fuel entrance. This filter is not normally designed to be serviceable or the only fuel system filtration device. Its main purpose is to prevent initial fuel line and rail contaminants from entering the injector. It also provides contamination protection during testing or servicing of the fuel system. An in-line serviceable filter functions as the primary fuel system filtration device. These filters usually have the capability of removing smaller contaminants than filters used on carbureted systems.

From the inlet filter section, the fuel moves to the fuel metering portion of the injector. The metering of fuel is accomplished by a valve and seat in conjunction with a metering orifice. On energization of the coil, magnetic force pulls the valve away from the seat allowing fuel to pass through the valve/seat and out through the metering orifice. The Qs of the injector depends on the fuel pressure and the hydraulic losses of the fuel circuit. By design, the major restriction to flow is in the metering section. The metering orifice usually presents the largest pressure drop; however, most designs also rely on a pressure drop across the valve and seat. As the stroke or lift of the valve is varied, the Qs is changed and can be used as a means for the manufacturer to obtain the specified Qs. A spring is incorporated to return the valve to the closed position when the coil is de-energized. This ensures that the injector is normally closed and fuel can only flow on energization of the coil. The spring also affects the time required for the valve to open and close, which changes the injector dynamic characteristics. Many designs, therefore, provide the manufacturer with the ability to adjust the preload of the spring to obtain the dynamic set point flow.

Most designs use highly finished metal-to-metal surfaces to provide a leak tight seal and minimize flow shift due to life cycling. Metal also helps minimize changes in stroke when operated at extreme environmental temperatures. Ball/seat, mating conical surfaces and flat surface designs are in use (Fig. 2).

From the metering section, fuel flows out through some type of spray pattern generating feature. The spray is produced by the metering ori-

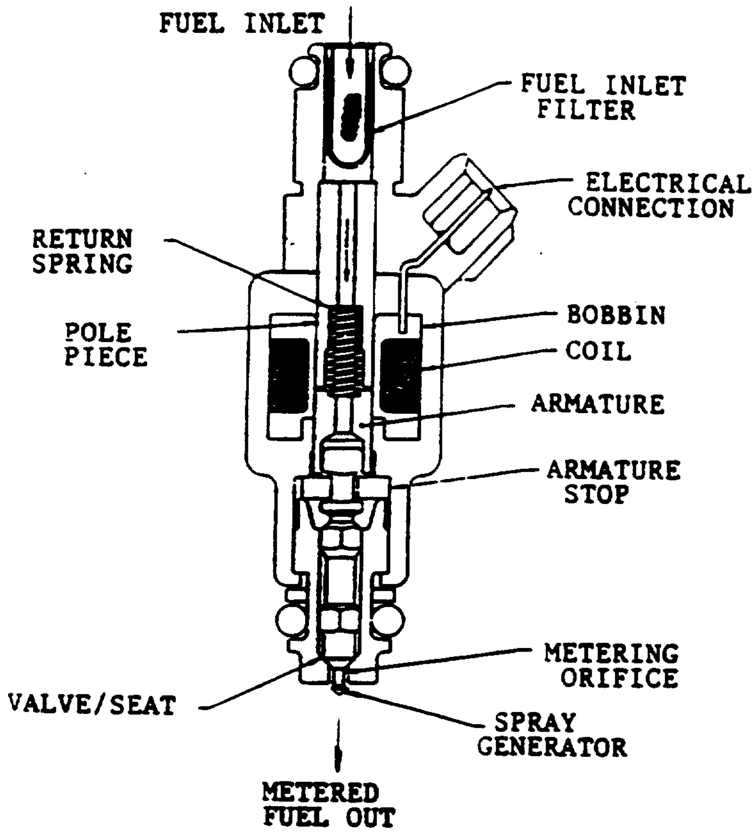


FIG. 1a—TOP FEED INJECTOR

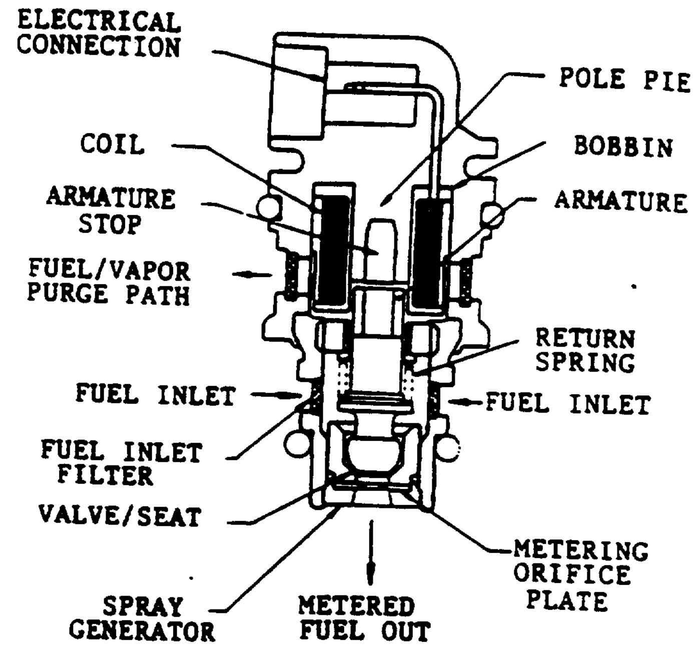


FIG. 1b—BOTTOM FEED INJECTOR

FIG. 1—TYPICAL FUEL INJECTOR DESIGNS

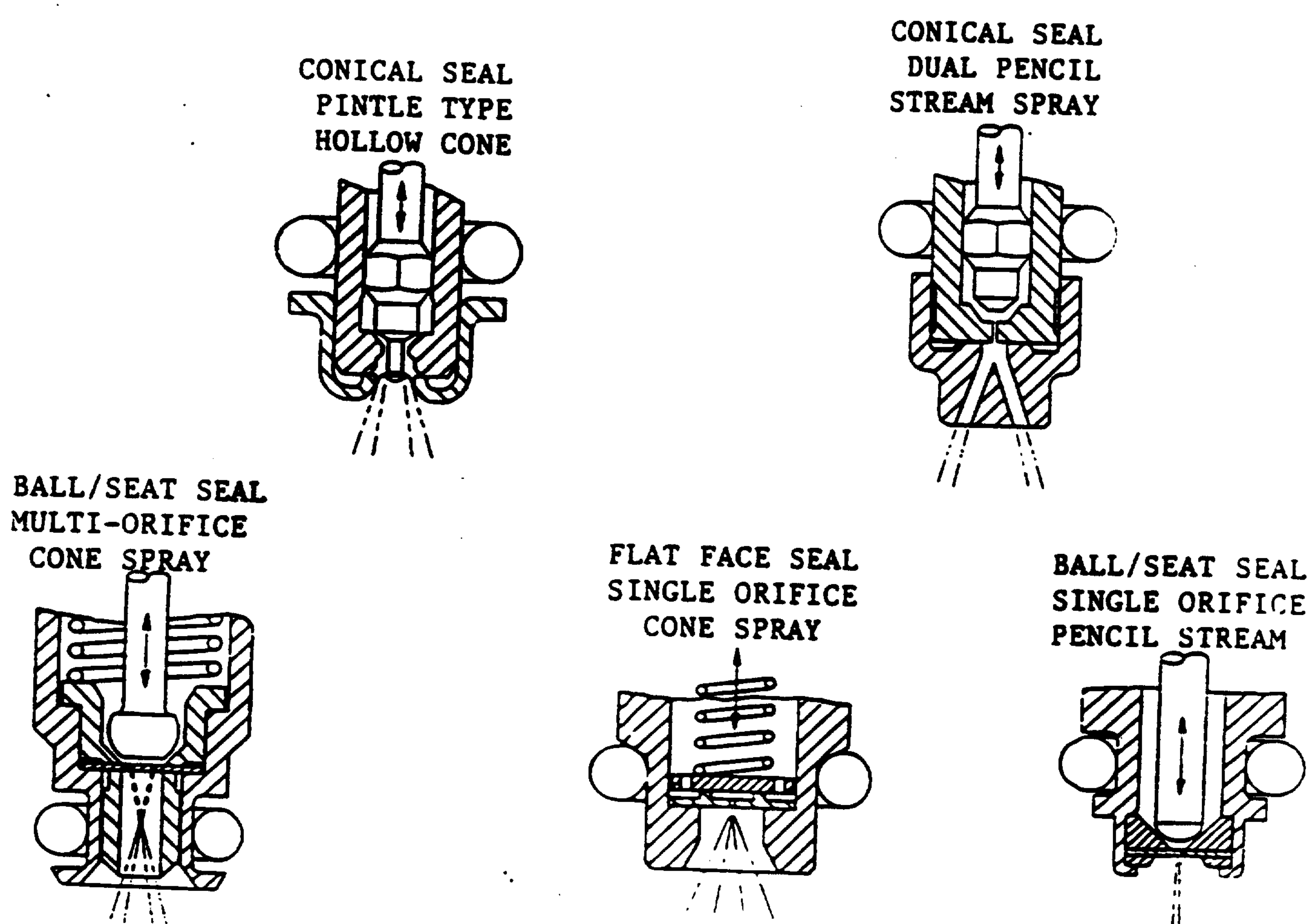


FIG. 2—FUEL METERING AND SPRAY GENERATION

fice or by a separate spray generating part. Injectors used for throttle body injection generally use multiple orifices to generate a wide angle, hollow cone. The current port fuel injection designs are more diversified in spray pattern generation. Multiple orifice, single orifice, and pintle styles exist. These generate patterns ranging from a pencil stream to cones of varying angle distribution. With the introduction of multiple intake valve per cylinder engine designs, dual stream port fuel injectors are sometimes used. Multiple sprays can target fuel to each inlet valve to promote more uniform air fuel mixture.

Top feed injector designs have the fuel traveling axially through the center of the coil and down into the metering area. This design is readily adaptable to PFI, but vapors generated within the injector are not easily purged due to the opposing incoming fuel flow. To minimize vapor generation and provide adequate hot fuel handling, the fuel system pressure is maintained at a relatively high level of 250 to 500 kPa.

Bottom feed injectors have been primarily used on central fuel injection systems where one or more injectors are located in the throttle body. This design allows packaging of an injector in a fuel metering body such that the injector is centered above the throttle plates. An advantage of bottom feed injectors is the incorporation of a vapor purge path. Since fuel comes in near the bottom of the injector, the fuel vapors can rise above the metering area. By providing a direct passage out of the injector, vapors are more easily purged. This vapor purge passage allows the use of lower fuel pressure (100 kPa) while still maintaining adequate hot fuel handling performance. Although typically used on central fuel injection applications, there is interest in using the bottom feed design for port applications.

2.2 Magnetic Circuit—The solenoid assembly of an electromagnetic fuel injector supplies the force to actuate the fuel metering valve. Two commonly used solenoid designs are the plunger style armature, the most prevalent, and the flat face disk armature. The major components of the solenoid assembly include the coil assembly, solenoid body, pole piece, armature, and return spring.

The function of the coil assembly is to produce a magnetic field when energized. The coil consists of a specified number of turns of insulated wire wound around a bobbin. The material and size of the wire is chosen to provide a given number of turns to develop the magnetic force while achieving the required electrical resistance for the injector driver circuit. Copper is typically used for low resistance injectors and brass for the high resistance injectors. The total electrical resistance of an injector is essentially equal to that of the coil assembly, which is a function of the resistivity of the wire, length of wire, and the termination of the wire to an electrical connector. Inductance, on the other hand, is a function of the number of turns in the coil, materials used for the body, armature, and pole piece, geometric construction, air gaps, etc. Inductance, therefore, must be measured on the completed assembly.

The magnetic field produced by the coil generates flux, which travels in a closed loop around the coil assembly. It is the function of the components in the magnetic path to carry the flux efficiently. The solenoid body is the segment of the circuit that carries flux from the pole piece to the armature. The armature is the moving element of the solenoid, which controls the flow of fuel by opening and closing a valve. The pole piece is the nonmoving element that attracts the armature when the coil is energized. The predetermined clearance between the pole piece and the armature is called the working air gap. It is through this air gap that the force of attraction is generated. The working air gap consists of both a fixed and a variable air gap, the latter of which is dependent on the position or stroke of the armature. The fixed air gap prevents contact between the armature and pole piece to minimize the effect of residual magnetism. Since contact between these two parts would result in longer closing times, a stop or spacer made from nonmagnetic material is used to ensure that a fixed clearance is maintained when the valve is fully opened. The magnetic force of attraction is most important in the working air gap; consequently the magnetic properties of the materials used and the geometry of the parts are critical to the performance of the design. The remaining parts of the magnetic circuit have a lesser effect on the total reluctance and response of the solenoid.

The major difference between the two solenoid designs shown in Fig. 3 is the path of the flux into the armature from the solenoid body. In the plunger design, radial and working air gaps are used. The radial gap is necessary to permit the armature to move axially relative to the nonmoving components of the solenoid assembly. The working air gap accommodates the motion of the armature assembly. In the flat face disk design, an additional working air gap is required with no radial air gap between the armature and solenoid body.

2.3 Cold Start Injector—The cold start injector is a simplified version of an electromagnetic top feed fuel injector used to provide additional fuel during crank at cold ambients. It is utilized primarily on PFI systems and is located in the inlet air passage to distribute fuel to all cylinders. It is normally energized by a bimetallic switch that provides battery voltage to the injector coil independent of the electronic control module or injector driver. Dynamic performance is not critical since it is operated only fully "on" or "off". Q_s, atomization of the fuel, and minimum operating voltage are the important criteria.

3. Standard Test Conditions—Unless otherwise specified, the following test conditions are implied:

3.1 Test Fluid—Fuel injectors are designed to spray gasoline, and most development and testing involves verification of injector performance with that fuel. Gasoline, however, is volatile and variable in physical properties. A less volatile hydrocarbon liquid (normal Heptane) with known physical properties and a viscosity and density near gasoline is, therefore, recommended for measurement of injector performance characteristics discussed in Section 4. It is recognized that no one test fluid is ideal and will duplicate the performance of multihydrocarbon fuels found in the field. n-Heptane was selected as the best compromise on the basis of (1) worldwide availability, (2) stability if reused, and (3) fluid properties close to that of gasoline. Tests that are more application-related or conducted for quality control, durability, etc., may be performed with fluids specified by the user.

n-Heptane is one of the two common pure hydrocarbons used to define the octane number scale, and is stocked in all petroleum refinery control and analytical laboratories worldwide to known levels of purity and consistency. It sprays with gasoline-like qualities through the known fuel injector designs, and yields excellent reproducibility of spray form and flow rates. n-Heptane is not gasoline, however, and flows in the most common injector design of 1987 at about 3 to 4% lower rate than Indolene, the U.S. EPA emission test gasoline (see Table 1). For different injector designs, other values of this gasoline to n-Heptane difference will be found.

The most significant advantage of n-Heptane over gasoline is reusability. It is a pure hydrocarbon compound and not a mixture of naturally occurring compounds, as in gasoline. Repeated flow testing, resulting in partial evaporation of the test fluid, does not change the flow properties of the remaining fluid. Thus, repeated flow measurements are more consistent. When correlation work with gasoline is carried out, the gasoline should be tested "once-through" the injector, and fresh gasoline used for replicate tests. In this way, property change in the gasoline due to partial evaporation will be avoided.

Both gasoline and n-Heptane are light, volatile liquids, and have flash points well below normal room temperature. Vapor from both liquids, therefore, poses a fire hazard that must be continuously controlled in the laboratory areas.

Factory-floor environments seldom permit routine use of flammable liquids above their flash points. Manufacture of fuel injectors generally involves a flow measurement of the completed (or partially completed) injector, and a heavier-than-gasoline liquid is usually chosen for this purpose, so that the flash point of the liquid is higher than the factory working area temperature. One such liquid is a typical medium petroleum distillate usually called "mineral spirits" in the USA, which has a flash point over 43°C. Such liquids require a laboratory-to-factory floor calibration step in which a flow rate on the test fluid corresponding to the desired gasoline flow rate must be established for each individual injector design and test condition. No general relationship is appropriate, or possible, from this document. Middle distillates for factory floor use are normally procured from convenient local facilities near the makers' plants, and valid-for-the-batch calibrations are made to determine and maintain production quality of the finished injectors. Physical

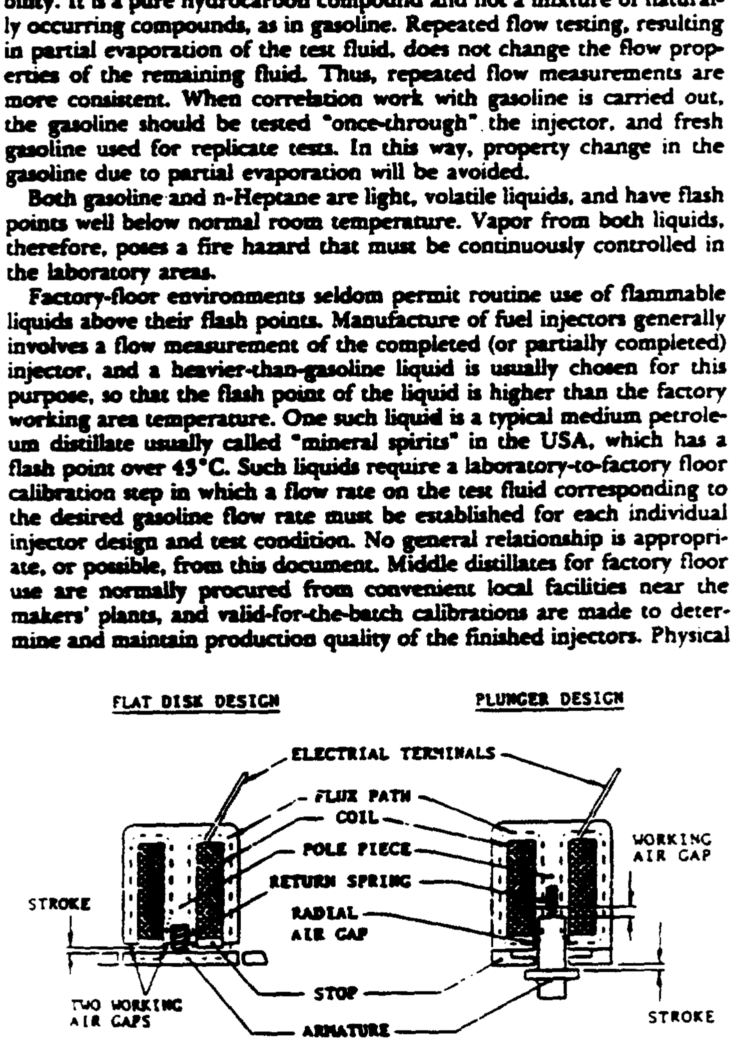


FIG. 3—MAGNETIC CIRCUIT

TABLE 1—INJECTOR FLOW RATES OF INDOLENE VERSUS n-HEPTANE

	Viscosity cSt @ 20°C	Specific Gravity	Static Flow g/s	Dynamic Flow mg/pulse
Indolene	0.619	0.75	1.993	3.63
n-Heptane	0.605	0.68	1.918	3.52
		% Difference	−3.8	−3.0

property specifications for n-Heptane, Indolene, and mineral spirits are given in Table 2.

3.2 **Fluid Temperature**—Should be measured at the injector inlet and stabilized at 20°C ± 1.0 (Reference 6.1).

3.3 **Injector Temperature**—Should be stabilized at room temperature 22°C ± 3 prior to test.

3.4 **Pressure**—The differential pressure across the injector will be determined by the application and held to within ±0.10 kPa of this value throughout the test. It should be specified in (kPa) units and measured at the injector inlet (Reference 6.1).

3.5 **Period (P)**—The time elapsed between the beginning of one injection pulse to the beginning of the next pulse shall be 10 ms/pulse ± 0.001 for both port and throttle body injection applications whether the fuel delivery method is simultaneous single or double fire, sequential, etc.

3.6 **Pulse Width (PW)**—The increment of time (ms) that the injectors are commanded to deliver fuel shall be determined by the type of test being conducted and held within ±0.001 ms.

3.7 **Injector Driver**—Determined by application and of instrument 4.1 for typical driver types). Voltage supplied to the driver shall be 14.0 V DC ± 0.05.

3.8 **Polarity**—Maintained constant throughout all testing and same as that used in the application.

3.9 **Test Apparatus**—The type of flow fixture used will vary depending on the particular injector parameter being evaluated (Reference Section 6).

3.9.1 Instruments—Stabilized per manufacturers' recommendations.

3.9.2 Injector Position—The injector should be mounted vertically cept when tested as an integral part of a fuel rail assembly.

3.9.3 Preconditioning—Purge injectors and test apparatus with test id to remove all air, vapors, and shipping fluids. Flow injectors for 000 pulses at 5.0 ms PW and 10 ms P. Discard purge fluid.

.9.4 Flow Measurement—Flow rate may be measured by either vol- e or mass flow with the latter being the preferred method. Data ould be reported in mass flow units (g/s or mg/pulse).

4. *Basic Characteristics and Definitions*

4.1 **Functional Parameters**—The following are parameters used in describing and/or measuring the basic functional characteristics of the injector.

4.1.1 Period (P)—The reciprocal of the frequency of injection; that is, the time elapsed between the beginning of one injection to the beginning of the next injection, expressed in units of (ms/pulse).

4.1.2 Pulse Width (PW)—Increment of time that the injectors are commanded to deliver fuel for a single injection event (ms).

4.1.3 Static Flow Rate (Q_s)— The rate of fuel delivered (g/s) by an injector when energized in the fully opened position. It is the maximum flow rate of the injector and can be used to approximate the slope (m_a) of the injector flow curve (Reference 4.1.11).

4.1.4 Dynamic Flow (Q_d)—The measured fuel delivered per pulse of the injector (mg/pulse) when energized at a specified pulse width: that is the actual quantity of fuel delivered during dynamic operation.

.5 Dynamic Flow Rate (Q)— The fuel delivered per unit of time energized at a specified PW and P. This term is used to indicate flow rate of the injector in units of (g/s).

$$Q = Q_d/P \quad \text{(Eq.1)}$$

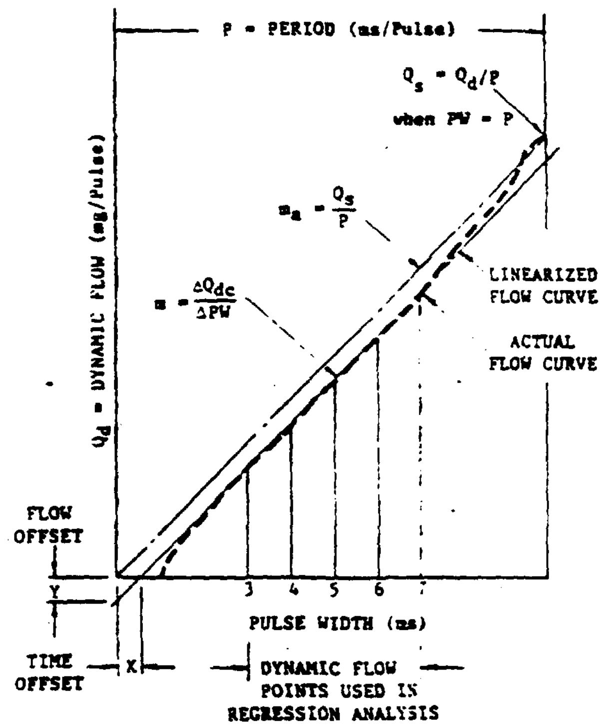
4.1.6 Dynamic Flow Calculated (Q_{dc}) —The calculated fuel delivery per pulse of the injector at a given pulse width based on the calculated (linearized) flow curve specified in mg/pulse.

$$Q_{dc} = m(PW) - Y = m(PW - X) \quad \text{(Eq.2)}$$

.7 Dynamic Set Point (PW_{sp}) —The pulse width specified in (ms), at which a specified fuel delivery is set during manufacture of the injector. It establishes Qsp, the dynamic performance and offset characteristics of the injector. It represents a Q_d point or pulse width at which the flow variation of a population of injectors is minimized.

4.1.8 Dynamic Set Point Flow (Qsp) —The measured fuel deli per pulse of the injector in mg/pulse when energized at the dy set point. This flow is used for incoming inspection and quality co

4.1.9 Linearity Deviation (LD)— Ideally, the flow from an inj should be linear and directly proportional to pulse width over th flow range of the injector. This is not the actual case, for significar viation from linearity occurs at the extremities of the flow curve (4 and 5). In order to measure the deviation from linearity, a squares regression analysis is performed on five intermediate points at 3, 4, 5, 6, and 7 ms PW with a period of 10 ms/pulse. Qd PW are, respectively, the dependent and independent variables. resulting curve is referred to as the linearized flow curve. Devi



DYNAMIC FLOW CALCULATED (mg/Pulse) = Q_{dc} = m(PW) − Y = m(PW−)

DYNAMIC FLOW RATE (g/s) = Q = Q_d/P

FIG. 4—CHARACTERISTIC INJECTOR FLOW CURVE

from linearity is then defined as the percent difference between the measured or actual flow (Q_d) and calculated flow (Q_{dc}) taken at a given pulse width divided by the calculated flow.

$$LD = \frac{Q_d - Q_{dc}}{Q_{dc}} \times 100 = \% \quad \text{(Eq.3)}$$

4.1.10 Slope (m)—The change in Q_d per unit of pulse width based on the calculated linear regression flow curve (mg/pulse/ms).

$$m = \frac{\Delta Q_{dc}}{\Delta PW} \quad \text{(Eq.4)}$$

4.1.11 Slope Approximated (m_a)— An approximation of the injector flow curve m using the Q_s expressed in units of (mg/pulse) when the P and PW are equal (see Fig. 4).

$$m_a = Q_s/P \quad \text{(Eq.5)}$$

When: Q_s = (mg/pulse) and P = PW (ms)

4.1.12 Time-offset (x)—The displacement of the calculated linear regression flow curve from the origin along the abscissa or pulse width axis (Fig. 4).

4.1.13 Flow-offset (Y)—The displacement of the calculated linear regression flow curve from the origin along the ordinate or Q_d axis (Fig. 4).

TABLE 2—PHYSICAL PROPERTY SPECIFICATIONS FOR TEST FLUIDS

PROPERTY	TEST FLUIDS		
Name of Fluid	Normal Heptane (CP Grade)	Indolene* (Clear)	Mineral Spirits
Purpose of Fluid	Primary reference fuel grade pure hydrocarbon liquid in gasoline boiling range, for injector flow tests in engineering and development.	Engineering and emission test gasoline for injector tests that require a full-boiling gasoline.	Middle distillate for production floor quality control tests.
Specific Gravity at 15.6°C (60°F) (ASTM D 1298)	0.681 to 0.685	0.739 to 0.749	0.775 to 0.785
Kinematic Viscosity at 20°C (68°F) (ASTM D 445)	0.60 to 0.64 cSt	0.59 to 0.65 cSt	1.195 to 1.205 cSt
Absolute Viscosity at 20°C (68°F) (ASTM D 445)	0.418 cps	0.418 to 0.468 cps	0.94 to 0.96 cps
Flash Point (typical) (ASTM D 56)	−1°C (30°F)	−40°C (−40°F)	43.3°C (110°F)
Distillation (ASTM D 86)			
Initial	97.7°C (208°F)	24 to 35°C (75 to 95°F)	150°C min (300°F)
10% Evaporated		49 to 57°C (120 to 135°F)	—
50% Evaporated	98.4°C (209°F)	93 to 110°C (200 to 230°F)	—
90% Evaporated		149 to 163°C (300 to 325°F)	—
End Point	99.4°C (211°F)	213°C max (415°F)	210°C max (410°F)
Pentane Insolubles (ASTM D 893) % by weight	0.001 max	0.001 max	0.01 max
Water Content (ASTM D 1744) % by weight	0.001 max	0.001 max	0.10 max

*Trademark of Amoco Oil Co.

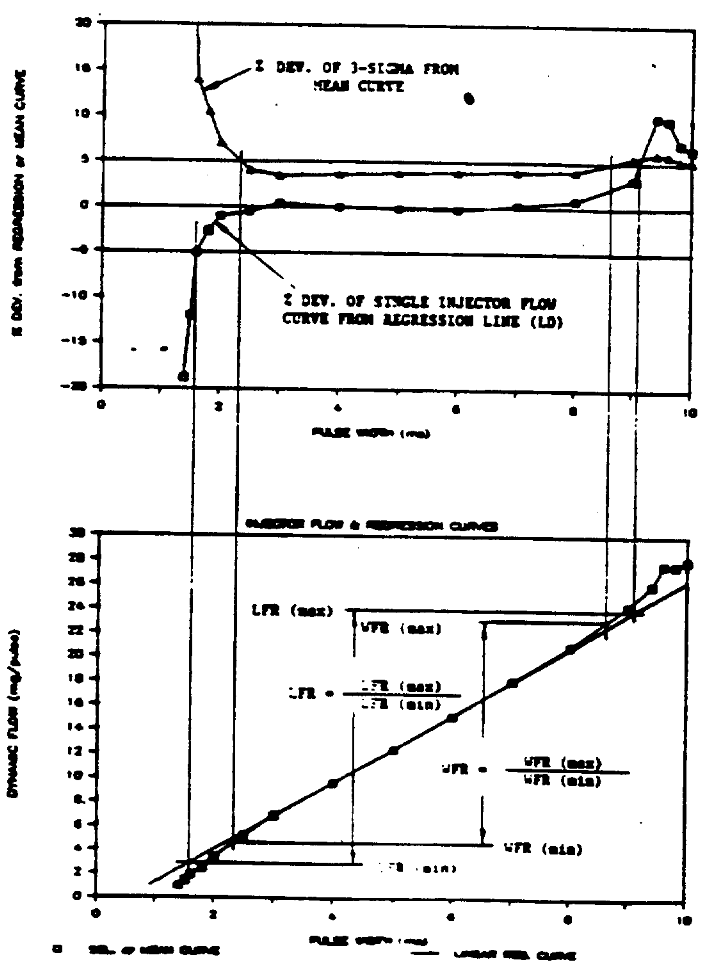


FIG. 5—CALCULATION OF FLOW RANGE

4.1.14 FLOW RANGE (LFR and WFR)—One of the more important characteristics of an injector is the usable minimum and maximum fuel flow. Flow range, specified as a ratio of the maximum to minimum dynamic flows, is used as a measure of this capability. Two methods are used for calculating the ratio: LFR and WFR.

4.1.14.1 *Linear Flow Range (LFR)*—A number based on the linearized flow curve of a single injector. It is used to compare the linear range between injectors of different design or manufacture. The number is defined as the maximum linearized flow point LFR (max) divided by the minimum linearized flow point LFR (min) at their respective pulse widths where the measured flows deviate ±5.0% from the linearized flow curve (see Fig. 5).

$$\text{LFR} = \frac{\text{LFR (max)}}{\text{LFR (min)}} \qquad \text{(Eq.6)}$$

4.1.14.2 *Working Flow Range (WFR)*—A number based on the mean flow curve of a population (24 minimum) of injectors representative of a normal production distribution. The application engineer is interested in this ratio, since it provides a relative measure of production injector-to-injector variability; that is, the flow range where a population of injectors will be within a specified tolerance. It is defined as the maximum working flow point WFR (max) divided by the minimum working flow point WFR (min) where all injectors are within ±5.0% of the mean flow curve at three standard deviations (see Fig. 5).

$$\text{WFR} = \frac{\text{WFR (max)}}{\text{WFR (min)}} \qquad \text{(Eq.7)}$$

4.1.15 REPEATABILITY—Ideally a measure of the pulse-to-pulse flow rate variation of the injector. It is an important element from the standpoint of engine control for emissions. The equipment required to accurately determine the mass flow for one injection pulse is expensive and resolution is limited. The following procedure is, therefore, recommended as a compromise:

The injector is tested at standard conditions at two points on the flow curve: (1) the Q_s, and (2) the 2.5 ms Q_d point. A minimum of 30 tests is conducted at each test point. Repeatability, given in percent, is then defined as:

$$\text{Static Repeatability} = \frac{Q_s\,(\text{max}) - Q_s\,(\text{min})}{Q_s\,(\text{avg})} \times 100 = \% \qquad \text{(Eq.8)}$$

$$\text{Dynamic Repeatability} = \frac{Q_d\,(\text{max}) - Q_d\,(\text{min})}{Q_d\,(\text{avg})} \times 100 = \%$$

4.1.16 STABILITY (S)—S is a measure of the variation in injector OT and CT and is an indirect measure of pulse-to-pulse performance or repeatability. It is determined by using a storage oscilloscope and observing the trace representing the OT and CT per 4.1.17. A timer can also be used to directly measure the elapsed time of the opening and closing events by triggering it at the initiation of the injector control pulse. Resolution should be adjusted such that variations of 10 μs can be discerned. Opening and closing times should be recorded for a minimum of 1000 consecutive pulses and the range stated in microseconds. Fig. 6 shows a typical measurement of closing time instability.

4.1.17 OPENING AND CLOSING TIME —The opening time (OT) of an injector is a measure of the time required for the injector armature to first reach its fully opened positioned after initiation of the driver circuit pulse input. Closing time (CT) is the time required for the injector armature to first reach its fully closed position after the termination of the driver circuit pulse input. Both OT and CT are recorded in (ms). They provide a relative indication of the combined mechanical and coil response time. The total time to open and close the injector orifice also provides a relative measure of the usable pulse width range of the injector. Fig. 7a shows a typical trace when using a peak-hold driver with an injector of low R. Fig. 7b shows a typical trace when using a saturated driver and an injector with high R.

The preferred method of measuring the opening/closing time interval is by the use of a precision accelerometer mounted within 2.5 cm of the injector body and a suitable time measuring instrument. The accelerometer may be mounted on either the injector body or on the fixture as shown in Fig. 8.

Alternate methods, though less accurate, include the use of a dynamic pressure transducer for both opening and closing, the inflection in the current trace for opening only, and the inflection in the voltage trace for closing only (Reference Figs. 6 and 7).

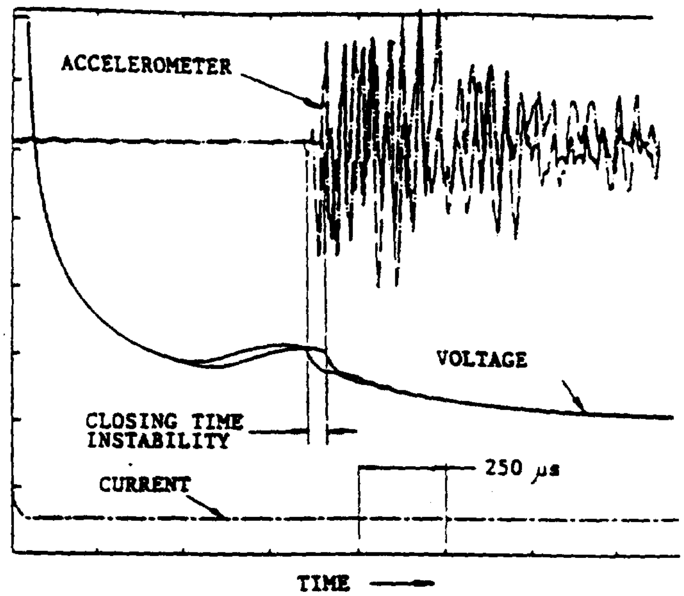


FIG. 6—MEASUREMENT OF CLOSING TIME INSTABILIT

4.1.18 COIL RESISTANCE (R)—Measurement of R permits the inject user to determine the current requirement for a given system voltag Presently, injector solenoid designs consist of either high or low resi tance coils. The high resistance design is typically 12 to 16 Ω and use with a saturated circuit driver. The driver turns battery voltage on an off allowing current to be controlled by the R. The low resistance de sign is typically 1 to 4 Ω and uses a current limiting driver. This syster allows a peak current for rapid opening response followed by a lowe current level, called the hold current, for the remainder of the com mand pulse.

The recommended measurement technique is by direct current witl the injector at a uniform temperature of 20°C ± 1. The four-wir method is preferred. A two-wire measurement is acceptable if measur ing leads are zeroed. The unit of measurement is to be the ohm witl a measured accuracy of ±0.01 Ω.

4.1.19 COIL INDUCTANCE (L)—The inductance of an electromagnetic solenoid is a function of the number of turns in the solenoid coil and the permeance of the magnetic circuit. Inductance is an indirect measure of the material properties and geometry of the flux path. Its value is, therefore, meaningful as a production control parameter.

Inductance, together with R, provides the time constant when the voltage is known and can be used in predicting the initial current rise profile.

The recommended method of measurement is with the injector in the closed or unenergized position using a Wheatstone Bridge or equivalent connected in a four-wire series mode. The standard test frequency used is 1.0 KHz + 0.5% with a potential of 1.0 V rms. The unit of measurement is the millihenry with a reported resolution of ±0.01 mH.

4.1.20 SPRAY PATTERN AND DISTRIBUTION —One function of the fuel injector valve is to break up the fuel into fine droplets. The engine's combustion process requires vaporization of the gasoline for proper combustion. Fine droplets increase the surface area to volume ratio of the gasoline, which reduces the time for the gasoline to vaporize.

The control of the spray pattern characteristics is important for all types of fuel injection systems. The spray pattern targets fuel to optimize transportation and vaporization. The radial and segmental fuel distributions are the characteristics specified to define the spray pattern.

Multipoint fuel injector designs can have single or multiple sprays with varying cone angles. Sprays less than 8 deg included angle are normally referred to as pencil stream. The larger spray cone angles range from 8 to 30 deg included angle. The spray cone fuel distribution can be hollow with the majority of the fuel in the outer cone surface or solid with a fairly uniform distribution of fuel within the cone angle.

Throttle body fuel injectors typically have a hollow spray cone pattern ranging from 40 to 60 deg included angle. The spray cone angle is specified to target the fuel with respect to the throttle plate.

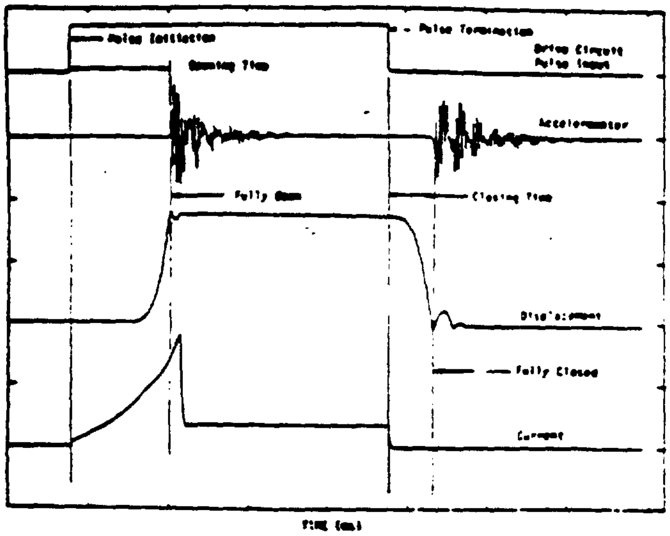


FIG. 7a—TYPICAL OPENING AND CLOSING TIME WITH PEAK AND HOLD DRIVER

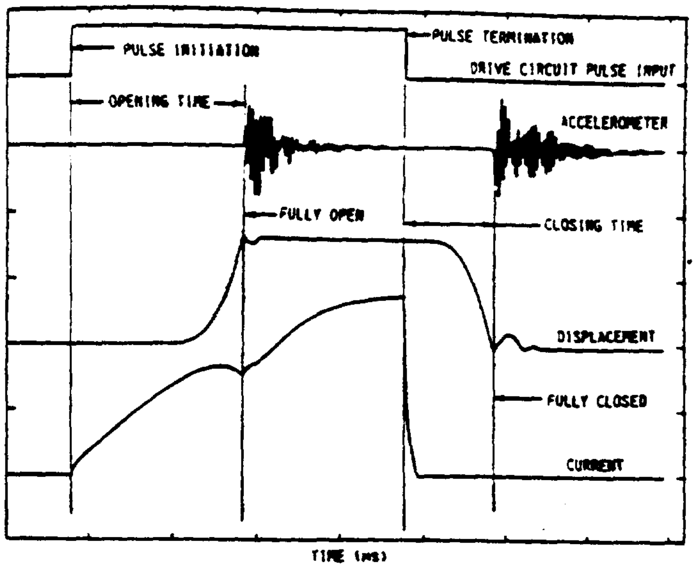


FIGURE 7b - Typical Opening and Closing Time With Saturated Driver

FIG. 7—OPENING AND CLOSING TIME

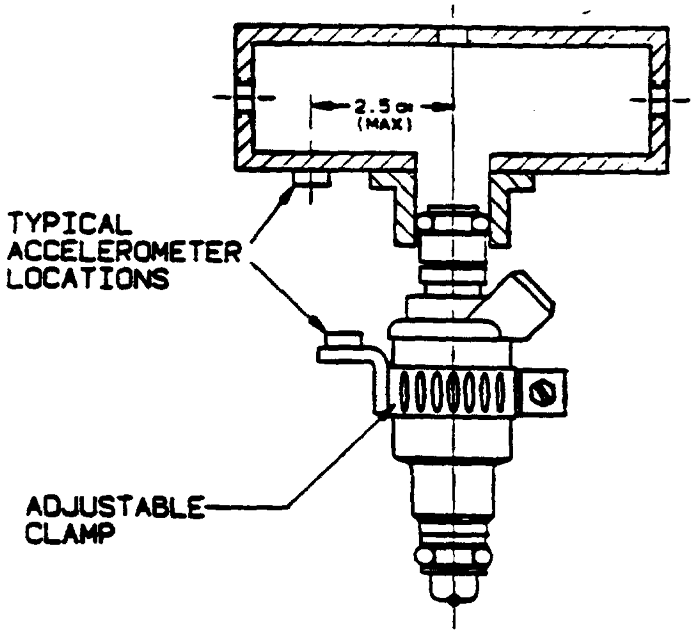


FIG. 8—ACCELEROMETER MOUNTING LOCATIONS

Radial spray characteristics are defined by the included angle and the distribution of fuel within that angle. The test fixtures shown in Figs. 9-14 illustrate the recommended method of measuring the spray cone angle and distribution of fuel within the pattern as measured in still air. The spray cone angle for a hollow spray cone pattern is defined as the included angle where the maximum concentration of fuel spraying from the injector is contained (Fig. 11). The spray cone angle for a solid spray cone pattern is defined as the included angle where 95% of the fuel spraying from the injector is contained (Fig. 12).

The collection vessel used to measure spray angle (Figs. 9 and 10) consists of eight concentric circular chambers. The walls separating the chambers are 15 mm high and have a tapered leading edge to minimize rebound of the spray.

A pencil stream injector does not distribute liquid into a cone of significant angle. This test fixture is, therefore, inappropriate for testing sprays of less than 8 deg included angle and should be replaced by a high-walled vessel to reduce spray rebound.

The collection vessel used to measure spray distribution (Fig. 13) consists of six equally spaced wedge shaped chambers separated by 15 mm high walls with tapered leading edges. Fig. 14 shows a recommended method for mounting the injector, spray collectors, and burettes.

Specifications for testing spray cone angle and fuel distribution for other types of systems are not discussed since these systems are still under development.

4.1.20.1 *Spray Measurement Procedure:*

a. Tests to be conducted with n-Heptane as the control fluid.
b. Tests to be conducted at pressure specified by application.
c. Tests to be conducted both at the dynamic set point pulse width and Q_s.
d. The collection vessel must be located below the point of origin of the injector's spray cone angle as indicated in Table 3 and Fig. 10. This distance is determined by the application. The point of origin of the spray cone angle must be specified from the injector's mounting surface datum.
e. The fuel injector must be centered over the collection vessel. The centerline of the injector mounting diameter datum must be held to within 0.025 mm of the true position of the concentric ring collection vessel's centerline.
f. To provide repeatable readings, the test fixture must be thoroughly wet down by pulsing the injector a minimum of 10 000 pulses. The fuel may be collected from the fixture drain holes in burettes for volumetric comparison or weighed for mass comparison.
g. The distribution of fluid for spray angle and radial distribution shall be defined by the user.

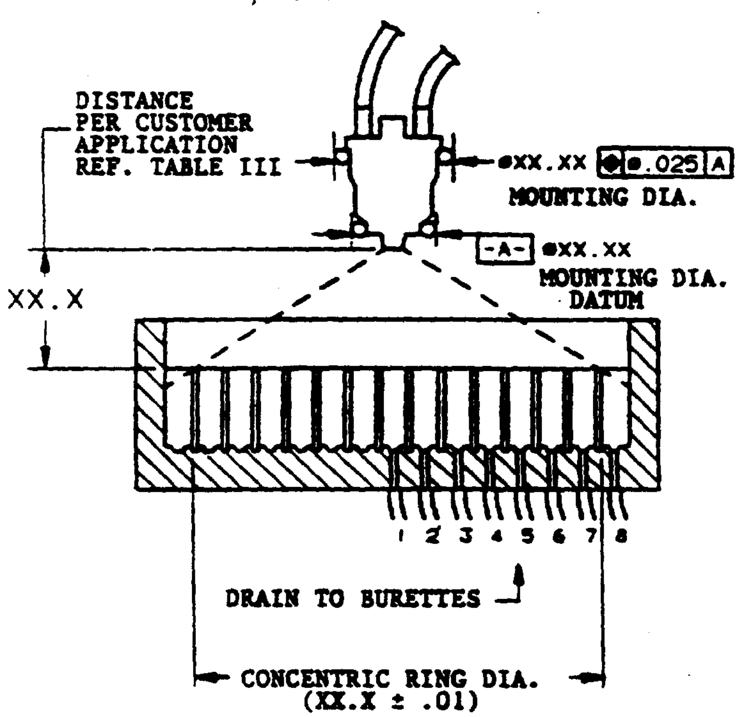


FIG. 9—RADIAL SPRAY COLLECTION VESSEL

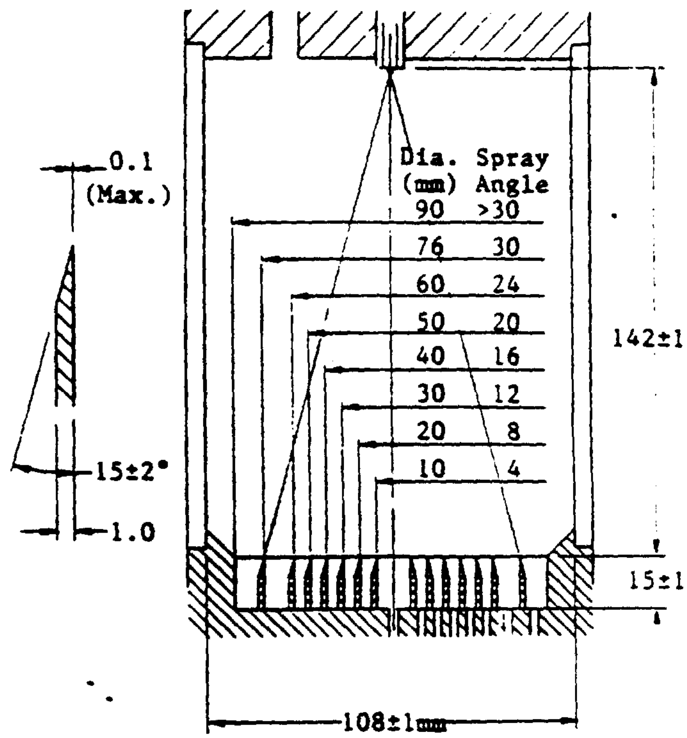


FIG. 10—TYPICAL SETUP FOR 30 DEG CONE SPRAY

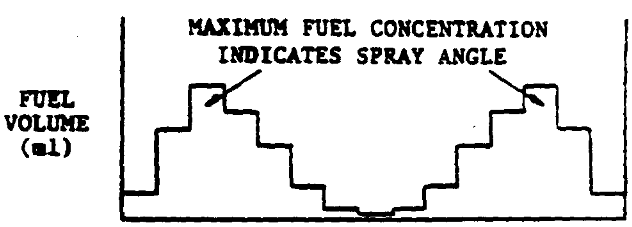


FIG. 11—TYPICAL FUEL DISTRIBUTION OF WIDE ANGLE HOLLOW CONE SPRAY

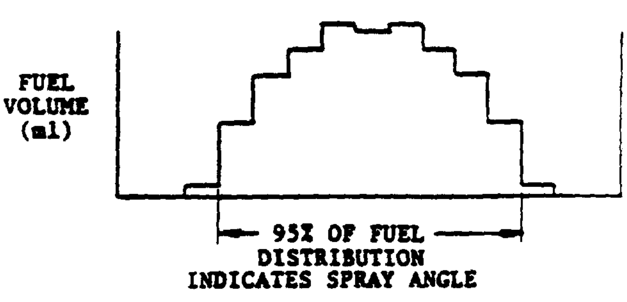
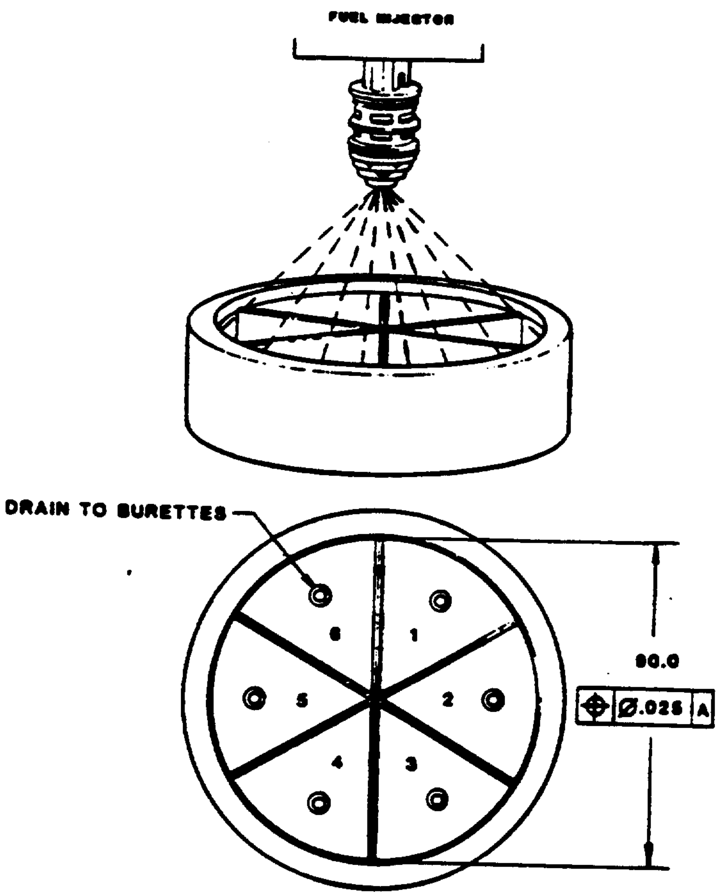


FIG. 12—TYPICAL FUEL DISTRIBUTION OF SOLID CONE SPRAY

TABLE 3—INJECTOR LOCATION AND CORRESPONDING SPRAY ANGLE

Ring No.	1	2	3	4	5	6	7	8
Diameter (mm)	10.0	20.0	30.0	40.0	50.0	60.0	76.0	90.0
Height (mm)	SPRAY CONE ANGLE (DEG)							
142.0	4.0	8.1	12.1	16.0	20.0	23.9	30.0	>30.0
91.7	6.2	12.4	18.6	24.6	30.5	36.2	45.0	>45.0
65.8	8.7	17.3	25.7	33.8	41.6	49.0	60.0	>60.0
38.0	15.0	29.5	43.1	55.5	66.7	76.6	90.0	>90.0



NOT APPROPRIATE FOR PENCIL STEAM INJECTORS

FIG. 13—SEGMENTED SPRAY COLLECTION VESSEL

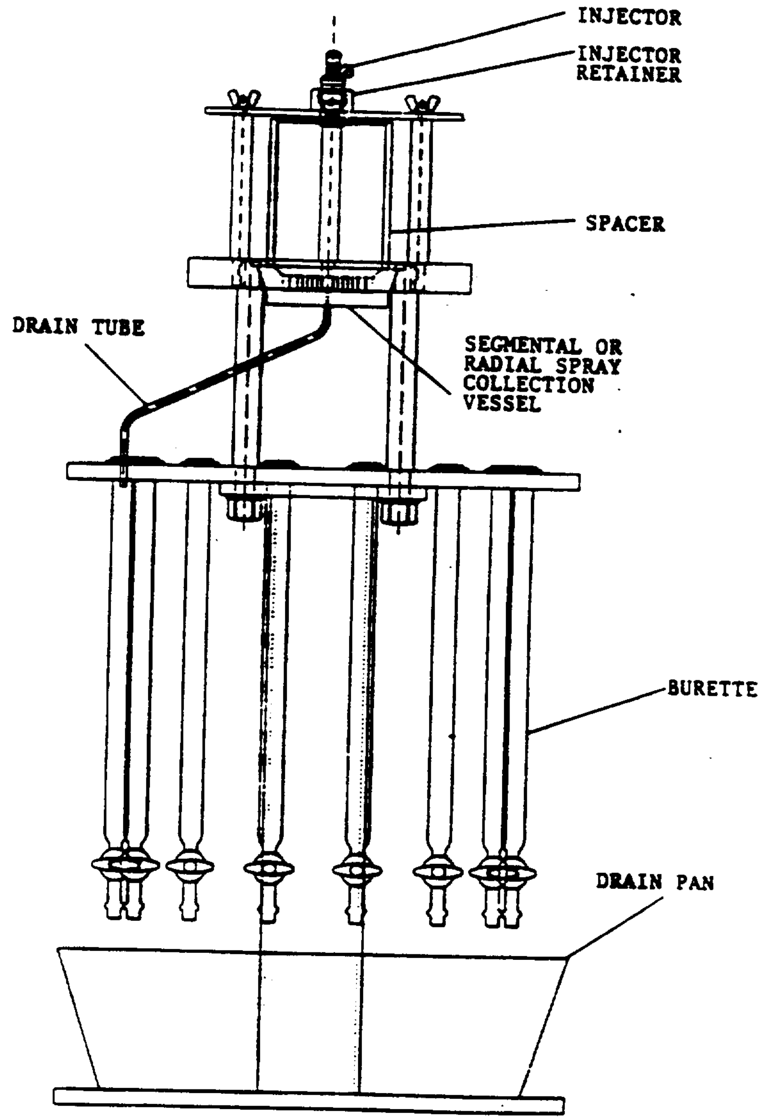


FIG. 14—SPRAY DISTRIBUTION TEST FIXTURE

4.1.21 External Leakage—No visible fluid leakage at working pressure is permitted in any area other than the seat. This includes the body, its seals, and the external O-rings.

The injector seat generally has metal-to-metal sealing surfaces for durability reasons. A leak tight interface is required between the mating surfaces of the injector valve seat components to maintain fuel pressure, prevent abnormal fuel accumulation in the intake manifold, and reduce deposit formation at the injector orifice. Seat leakage may result in a leaner or richer A/F ratio depending on such variables as leakage rate, temperature, and soak period.

Loss of pressure during extended periods of engine shutdown under hot ambient conditions may cause excessive fuel vaporization and incorrect fuel delivery during start-up. The increased time required to achieve desired rail pressure in combination with vapor entrained in the fuel delivered can result in increased cranking time, rough idles, stalls and/or a no-start condition.

Fuel leakage into the intake manifold may cause a richer than normal A/F ratio during start-up. Engine emissions may be adversely affected under these conditions. Even slight seepage may increase deposit formation at the metering orifice of the injector. Deposits so formed can partially plug the orifice and reduce the fuel delivered, which adversely affect both vehicle emissions and driveability (see 5.4).

Seat leakage can be specified as either a test fuel leak rate or a gas leakage rate. The preferred method is the use of dry nitrogen as the test medium.

4.1.21.1 *Seat Leakage Test Procedure*—The injector must be in a clean and dry condition in order to obtain an accurate repeatable leakage test. All liquid test fluid contained in the injector must be removed, since a nonexisting tightness is simulated if the seat is moistened.

4.1.21.1.1 Drying Procedure—

a. Flush injector with n-Heptane per preconditioning procedure 3.9.3.
b. Apply dry nitrogen at 60 kPa to the inlet of the injector with the tip pointing down.
c. Dry injector by actuating at a PW of 2.5 ms and 5.0 ms P for a minimum of 6000 pulses (30.0 s).
d. Orient injector with tip pointing up.
e. Dry injector again for 30.0 s using dry nitrogen at 60 kPa while the injector is actuated at 2.5 ms PW and 5.0 ms P.

4.1.21.1.2 Measurement Procedure—

a. Measure the leakage rate using any highly sensitive gas volume sensor. An acceptable method is to immerse the injector with its tip pointing up into a container filled with mineral spirits or equivalent.
b. Suspend the mouth of a graduated cylinder previously filled with test fluid above the tip of the injector.
c. Apply dry nitrogen at 20°C ± 1 within ±2% of system pressure to the injector inlet for 5 min with the injector valve seat closed.
d. The collected bubbles represent the injector air leak rate. The permissible leakage is dependent on the application (normally less than 1.5 cc/min).

4.1.22 Operating Voltage Range—Under certain circumstances, such as cold engine cranking, normal operating voltage is not available. The minimum opening voltage of the injector is especially critical for high resistance injectors as the coil current is directly proportional to the available voltage. Low resistance injectors are not as sensitive to lower battery voltage due to the current limiting driver circuit characteristics (Fig. 15).

4.1.22.1 *Static Minimum Operating Voltage (SMOV)*—This is the voltage, measured at the injector electrical connector, at which the injector opens as determined by an accelerometer or other sensing device capable of detecting the commencement of fluid flow.

4.1.22.1.1 Test Procedure:

a. Mount the injector in the test fixture under the standard test conditions per Section 3.
b. While measuring the voltage at the electrical connector, raise the supply voltage in 0.10 V steps every 20.0 ms.
c. Record the voltage when the injector opens.

4.1.22.2 *Dynamic Minimum Operating Voltage (DMOV)*—This parameter is a measure of the fuel injection systems response to low voltage conditions. The driver circuit has a significant effect on the injector response characteristics; therefore, the driver circuit as used in the vehicle must be used.

4.1.22.2.1 Test Procedure:

a. Mount the injector in the test fixture under the standard test conditions per Section 3.
b. Using the driver circuit from the vehicle application, raise the supply voltage to the driver in steps of 0.10 V starting at the SMOV. The logic pulse to the driver is to be a period of 20.0 ms and a PW of 10.0 ms. A minimum of 1000 pulses are to be supplied at each step.
c. Measure the supply voltage and the injector flow rate at each step point.
d. The DMOV is that voltage at which the flow rate exceeds 50% of the flow at 14.0 V.

This test may also be modified to generate a voltage compensation curve for the system by continuing readings beyond the minimum opening point and using other PWs to create the family of curves similar to those in Fig. 15.

4.1.22.3 *Maximum Overload Voltage*—The injector must maintain calibration after a maximum of 24.0 V is applied to the driver for a period of 60 s. This test is intended to simulate an incorrect jump start condition.

The injector and driver are tested as an assembly with the injector operating at Q_s and system pressure. Test voltage must not be applied directly to the injector terminals for damage may occur.

4.1.23 Static Pull-in Current (I/S-ON)— I/S-ON is the minimum current required to actuate the injector from the closed to the open position. It can be used to calculate the SMOV if multiplied by the R and can be useful information in diagnosing functional problems and designing of injector driver circuits.

The recommended method of measurement is to increase current to the injector in a staircase waveform with a step height of 1.0 mA and a width of 10.0 ms until the injector opens as indicated by an accelerometer signal or other sensing device capable of detecting commencement of fluid flow. The injector must be mounted with the nozzle pointing downward and with system pressure applied to the inlet. Start test at 90% of anticipated I/S-ON current to avoid overheating the injector.

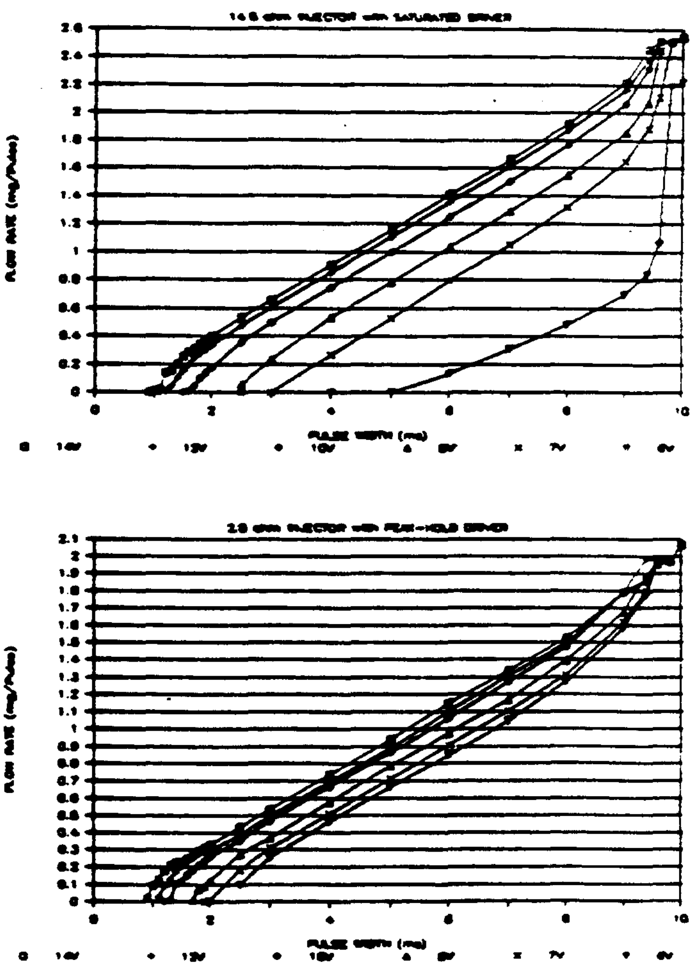


FIG. 15—EFFECT OF VOLTAGE ON PERFORMANCE

4.1.24 STATIC DROP-OUT CURRENT (I/S-OFF)—I/S-OFF is the minimum current required to hold the injector open after it has been energized. It is used to determine the holding current calibration of the peak-hold driver.

The recommended method of measurement is to apply sufficient current to assure that the injector is in the open position and then to decrease the current in a staircase waveform with a step height of 1.0 mA and a width of 10.0 ms until the injector closes as indicated by an accelerometer signal or other sensing device capable of detecting cessation of fluid flow. The injector must be mounted with the nozzle pointing downward and with system pressure applied to the inlet.

The I/S-OFF is always lower than the I/S-ON because the solenoid air gap is smaller by the amount of the stroke, which will yield higher magnetic forces for any given current level. The drop-out current is generally measured immediately following the pull-in current measurement.

4.1.25 PRESSURE DROP RATIO (PDR)—A ratio of the fuel pressure drop across the metering orifice of an injector compared to the fuel pressure drop across the valve seat.

The PDR is useful in evaluating the sensitivity of an injector design relative to the metering of hot fuel. Calculations can be made to determine if fuel exiting the metering area of the injector will vaporize if the PDR, fuel inlet pressure, fuel volatility, and maximum application temperature are known. This assumes that the valve/seat and the metering orifice are the primary restrictions to flow. If additional significant pressure drops occur within an injector design, they must be accounted for before any hot fuel handling predictions are made. Since an injector is designed to meter a liquid, fuel vapor cannot be accurately metered and steps to minimize this condition should be taken.

4.1.26 INSULATION RESISTANCE (IR)—This test is designed to check for a potential failure of the insulation between the coil assembly and the case of the injector. It is usually performed on completed injectors to ensure that the coil insulation has not been damaged during the assembly process and that the terminal to case clearance has been adequately maintained. IR is also measured after any mechanical integrity testing to ensure that the insulating abilities of the injector coil assembly have not been degraded.

In most existing applications, a positive battery voltage is continuously applied to one of the injector terminals and the unit is energized by completing the ground circuit. In a situation where the IR breaks down, the injector could become continuously energized and flood the engine. On systems that energize the unit by providing the positive voltage through the driver, breakdown can cause the injector to misfire or not fire at all depending on where the coil assembly is shorted.

4.1.26.1 *Test Procedure*—Connect a standard megaohmmeter tester, set to 750 V DC, between the injector case and a coil terminal post. The minimum allowable resistance reading shall be 340k Ω after 2 s.

5. Application Related Parameters and Tests

5.1 Injector Driver—An electronic circuit that supplies voltage pulses to an electromagnetic fuel injector for a precise increment of time and at a given repetition rate. The accuracy of these pulses and their repetition is normally ±0.001 ms. The peak-hold driver and the saturated driver are most commonly used by the industry for vehicle applications.

5.1.1 PEAK-HOLD DRIVER—A driver that uses two levels of current to operate the injector (Fig. 16). The driver circuit applies battery voltage to the injector until a predetermined current level is reached. The current is then reduced and held at a lower level for the duration of the PW. This type of driver is normally used with injectors having low resistance coils (typically around 2 Ω). The accuracy of the driver peak current level (I_p) and the hold current level (I_h) is held to ±0.50%. Note—In order to minimize OT instability, it is advisable to match the injector and driver characteristics such that the switch from peak-to-hold does not occur until after the injector is fully open.

ADVANTAGES: The high peak current minimizes OT response and the low hold current minimizes CT response. This method of control results in an increased linear range of injector operation.

DISADVANTAGES: Heat is primarily dissipated at the driver. Circuitry is more complex than that of the saturated driver.

5.1.2 SATURATED DRIVER—A power transistor driver that turns fully on for the entire duration of the injector PW (Fig. 17). This type of driver is used with injectors having high resistance coils (typically 12 to 16 Ω) or with injectors having low resistance coils in combination with a ballast resistor.

ADVANTAGES: Heat is primarily dissipated through the injector or ballast resistor and not at the driver circuit. Circuitry is simplified compared to the peak-hold driver.

DISADVANTAGES: The inherently slower dynamic response of this system decreases the injector's usable flow range. The Q of an injector used with this type of circuit is more duty cycle sensitive due to heat dissipation considerations. This driver's inductive suppression, which may be resistance-capacitance or zener, significantly affects the injector's Q_d rates due to variations in the circuit's current decay rate. This decay results in a change of the injector's closing time.

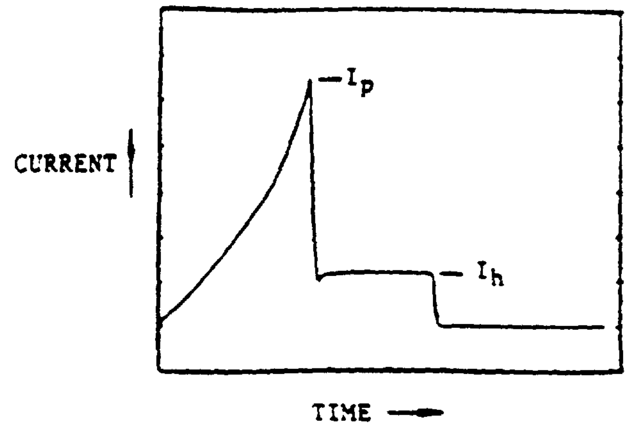


FIG. 16—TYPICAL INJECTOR CURRENT WITH PEAK-HOLD DRIVER

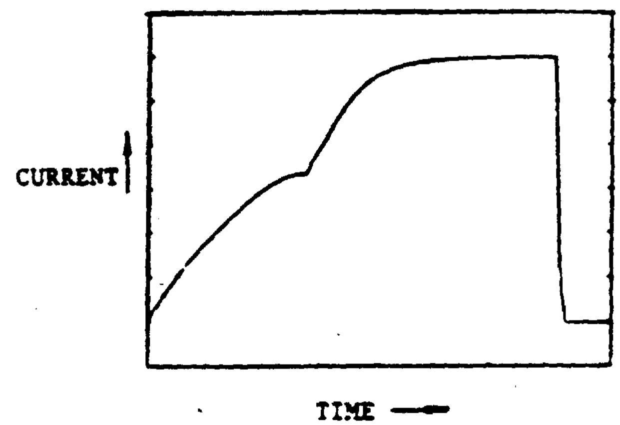


FIG. 17—TYPICAL INJECTOR CURRENT WITH SATURATED DRIVER

5.2 Firing Strategies—Both the peak-hold and the saturated drivers are used in various firing strategies. Three commonly used schemes are simultaneous double fire, sequential single fire, and alternating double fire (see Fig. 18).

5.2.1 SIMULTANEOUS DOUBLE FIRE (SDF)—A multipoint fuel delivery technique in which all injectors in a 4-cycle engine are energized simultaneously once per crankshaft revolution.

5.2.2 SEQUENTIAL FUEL INJECTION (SFI)— A multipoint fuel delivery technique in which each injector is individually energized and timed relative to its cylinder event. Fuel is delivered to each cylinder once per two crankshaft revolutions in 4-cycle engines and once per crankshaft revolution in 2-cycle engines.

5.2.3 ALTERNATING DOUBLE FIRE (ADF)—A multipoint fuel delivery technique in which the injectors are energized in groups once per crankshaft revolution.

5.3 Operating Temperature Range—This procedure is designed to evaluate injector performance when exposed to thermal conditions. Injector performance data is taken both before and after the prescribed thermal cycle to determine if any degradation has occurred as a result of the experienced temperature extremes and/or temperature cycles. Performance data for this test shall include, but not be limited to, Q_s, Q, IR and fluid leakage. The acceptable performance limits and the temperature levels used during testing are determined by the vehicle application.

5.3.1 HOT STATIC SOAK—Purge all fluids from the injector and expose it to a stabilized ambient temperature of 150°C ± 2 for 16 h. The injector is not operated during this test.

5.3.2 COLD STATIC SOAK—Purge all fluids from the injector and expose it to a stabilized ambient of −40°C ± 2 for 16 h. The injector is usually not operated during this test.

5.3.3 CYCLIC SOAK—Expose the injector to the hot thermocycle shown in Fig. 19 for a total of 140 cycles. The injector is to be operational only during segment D-E of the cycle, using a PW of 2 ms and a period of 7 ms. The test shall be run with indolene.

5.4 Injector Fouling in Service—Fuel injectors must retain their calibration while in use in order to retain satisfactory engine performance, driveability and emission control levels. Cleanliness of the injector metering orifices and spray-forming nozzles must be maintained in order for initial calibration to be dependable after extended use. Because this elementary requirement has not been universally achieved, fuel injected engines of today require careful choice of fuel supply, additive treatment, or periodic injector cleaning to achieve permanent flow stability.

A variety of injector design approaches to maintain calibration on "problem" fuels are being investigated as this document goes to press. Open-orifice injectors may maintain calibration better than annular-orifice types. All designers of injection systems today must ensure that their products are supported by a plan that will secure dependable operation by the users.

The major location of injector flow restriction due to dirt or deposit accumulation is in the tip area of high pressure multipoint electronic injectors. Unstable gasolines can, in multistop city driving, build up a varnish-like deposit on the injector tip. These deposits reduce fuel flow through the annular orifice and cause lean engine operation and all the attendant driveability faults. The faulty operation persists until the injectors are cleaned or replaced.

Cleaning of injectors in service can be accomplished with in-tank additives to fuel, by solvent-cleaning of installed injectors, or by ultrasonic cleaning of removed injectors.

Fuel chemistry can stop or reverse deposit accumulation in the injector tip area. Gasolines with low olefin content (as produced from refineries with no cracking units) seem immune to the problem. Gasoline with substantial levels of cracked or polymer components require careful additive treatment with detergent-dispersant chemicals to maintain injector cleanliness. Higher levels of these detergent-dispersant additives can reverse deposit buildup in service and clean injectors, which were deposit-restricted on other fuels. Some gasoline marketers in the United States identify such injector-cleaning gasoline formulations at the point of purchase.

Fuels with high levels of both lead alkyl antiknock and sulfur (>2.0 gPb/usg and >0.15% S) may plug injectors regardless of base fuel formation. High additive levels may always be required in such fuels and an injector of fouling-resistant design may be required.

5.5 Salt Corrosion—This test is to be applied to gasoline injectors to ensure that they can withstand the effects of external salt corrosion, which is likely to be encountered on seaside marine applications and salty road conditions (Reference ASTM B 117-85).

5.5.1 TEST PROCEDURE:

a. The injector shall have its inlet and outlet suitably sealed. The injector is to have its electrical connector fitted; however, it is not to be energized.
b. Samples shall be supported or suspended between 15 and 30 deg from the vertical, with any significant surface parallel to the principal direction of fog flow.

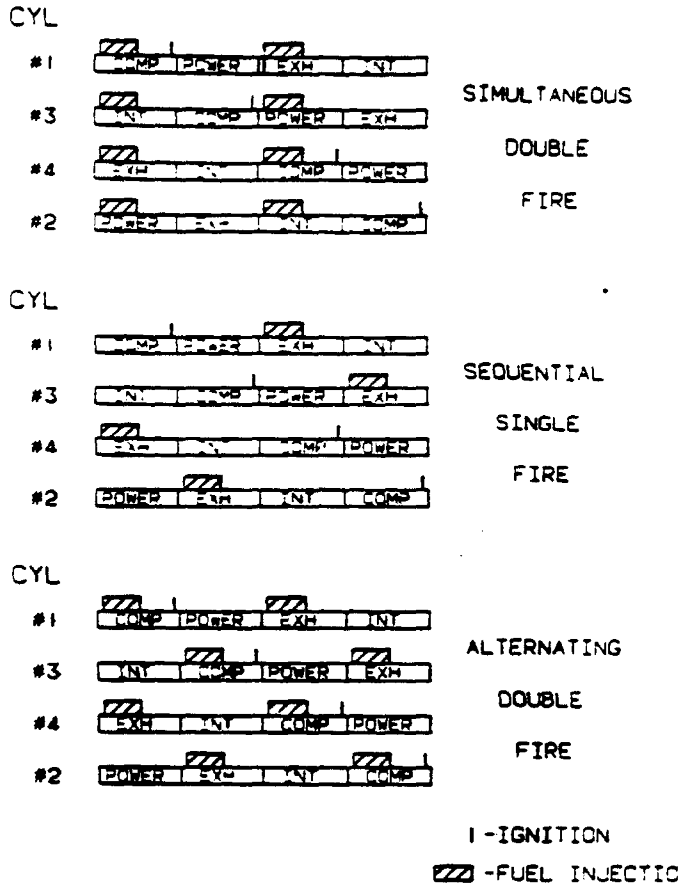


FIG. 18—PORT FUEL INJECTION FIRING STRATEGIES

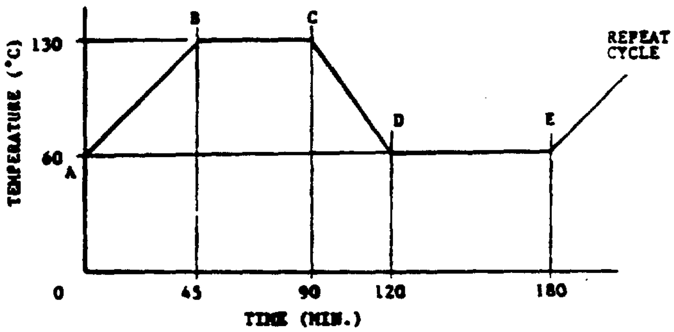


FIG. 19—THERMOCYCLE TIME SCHEDULE

c. Samples shall be at least 30 mm from each other and 35 mm from a chamber wall.
d. Sample shall be so placed as to permit free settling of fog on all samples, but avoid salt solution from one sample dripping onto another.
e. Expose the samples in the fog chamber for a period of 96 h. Inspect the samples and operation of the chamber as required. Opening of the chamber shall be limited to the frequency necessary to carry out the operations. Inspections should not be made more than twice a day for a total of 15 min. Position of the samples may be varied during the inspection period.
f. Remove the samples, wash gently in water not warmer than 38°C, and dry by blotting with absorbent paper.

5.5.2 Corrosion Assessment—Each injector tested shall be examined immediately after testing. The degree of corrosion shall be visually assessed in accordance with 5.5.3.

Each injector tested shall meet the performance requirements detailed in 5.5.4 prior to and after the completion of testing.

5.5.3 Surface Corrosion And Blistering—For the purpose of this document, a "significant surface" is defined as an area designated to be coated that can be touched by a 6.35 mm diameter ball.

Any spots of red rust on a significant surface shall be cause for rejection. Rust spots on surfaces, which cannot be touched by a 6.35 mm ball, shall be noted but will not be cause for rejection.

Any blistering of the coating shall be noted as to location on the sample piece, blistering size, and number of blisters. Blistering on significant surfaces shall be cause for rejection. An excess of three blisters of 1.0 mm diameter on surfaces, which cannot be touched by a 6.35 mm ball, shall be cause for rejection.

5.5.4 Performance Assessment—Each injector shall be tested for Q_s (4.1.3), Q (4.1.4), IR (4.1.26), R (4.1.18), and leakage (4.1.21) prior to and after completion of corrosion tests. Q_s and Q deviation shall be reported as a percentage (Reference 5.9.3).

5.6 Fluid Compatibility (External)—This test is to be applied to the external surface of a gasoline injector, excluding external O-rings, to ensure the external surfaces can withstand contact with common automotive fluids.

5.6.1 Test Fluids—It is not practical to evaluate all variations of test fluids, therefore, agreed reference fluids are employed in testing. The most commonly used fluids are listed as follows:

A reference fluid is defined as a material representative of its particular group, which is sufficiently well defined in all respects so that supplies from different sources are essentially identical in action for which the test is intended (Reference ASTM D 471-79).

ANTIFREEZE 50%—Shall be an ethylene glycol based material as described in SAE J814 mixed with an equal volume of water.

AUTOMATIC TRANSMISSION FLUID—Shall be Dexron II (General Motors Registered Trademark) or equivalent.

AXLE AND MANUAL TRANSMISSION LUBRICANTS—Gear Oil API-GL-5 as described in SAE J308. (Viscosity as defined in SAE J306 may be specified at the option of the test engineer.)

BATTERY ELECTROLYTE—Shall be reagent-grade sulfuric acid diluted with water to a specific gravity of 1.25 to 1.28.

BRAKE FLUID—Is a mixture of polyglycols and cellosolves conforming to DOT-3 of 49 CFR 571.116.

BUTYLCELLOSOLVE—Technical grade.

DIESEL FUEL (NO. 2)—As described by SAE J313. The fluid shall have an Aniline point of 60 to 70°C. It is preferred that emissions-grade diesel fuel conforming to 40 CFR 86.113-82 be used.

ENGINE OIL—Shall be ASTM Reference Oil No. 3.

INDOLENE—Shall be US EPA emission data fuel.

GASOLINE AND 20% METHANOL—Shall be 20% v/v reagent-grade methanol added to gasoline.

GREASE (LITHIUM SOAP BASED)—Shall be an extended-lubrication-interval grease as described in SAE J310. When tested to ASTM D 128, it shall contain not less than 4% by weight Lithium (12-Hydroxystearate type).

MINERAL SPIRITS—See Table 2.

1,1,1-TRICHLOROETHANE—Shall meet the requirements of Military Standard MIL-C-81533.

HIGH PRESSURE PULSED WATER—High pressure pulsed water, as found in commercial car washing machines, is to be sprayed over the exterior surfaces of the injector for 15 s. Note: Last step of 5.6.2 does not apply.

STEAM CLEANING—Steam cleaning, as found in commercial equipment, is to be sprayed over the exterior surface of the injector for 15 s. Note: Last step of 5.6.2 does not apply.

5.6.2 Test Procedure—Testing an injector with one fluid followed by another fluid is to be avoided.

a. Each injector shall have its inlet and outlet suitably sealed. The injector is to have its electrical connector fitted; however, it is not to be energized.
b. The injector shall have its exposed surfaces dampened either by spraying or brush application and allowed to stand for 24 h.
c. On completion of the 24-h period, the injector shall be degreased using 1,1,1-Trichloroethane or equivalent.

5.6.3 Assessment Of Results—Each injector tested shall be examined immediately after testing. The external surface condition shall be visually assessed in accordance with 5.5.3.

Each injector tested shall meet the performance requirements detailed in 5.5.4 prior to and after the completion of testing.

5.7 Fluid Compatibility (Internal)—This test is used to determine the compatibility of internal fuel injector components with fluids similar to those that may be found in the vehicle's fuel system.

5.7.1 Test Fluids—It is not practical to evaluate all test fluids, therefore, agreed reference fluids are employed in this test. The most commonly used fluids are listed.

A reference fluid is defined as a material representative of its particular group, which is sufficiently well defined in all respects so that supplies from different sources are essentially identical in action for which the test is intended (Reference ASTM D 471 79).

WATER/GASOLINE SOLUTION—Mix by volume, 98% unleaded gasoline and 2% corrosive water. Corrosive water is a solution formed by dissolving the following amounts of anhydrous sodium salts in one liter of distilled water at 40°C to aid the mixing:

Sodium Sulfate	14.8 mg
Sodium Chloride	16.5 mg
Sodium Bicarbonate	13.5 mg

GASOLINE AND 20% METHANOL—Shall be 20% by volume reagent-grade methanol added to unleaded gasoline.

GASOHOL—Shall be 10% by volume reagent-grade ethanol added to unleaded gasoline.

BUTYLCELLOSOLVE—Shall be 5% by volume technical-grade Butylcellosolve added to unleaded gasoline.

OXIDIZED GASOLINE (Sour Gas)—Shall be mixed by the following procedure to achieve a peroxide number of 180 millimole/liter:

a. Stock Fuel—Mix 70/30% by volume n-Heptane/Toluene
b. Copper Ion Stock Solution—Due to the hazardous nature of these chemicals, the solution must be prepared sequentially in the following three steps:

Note: FAILURE TO FOLLOW PROPER PROCEDURES CAN RESULT IN FIRE. REFER TO OSHA MATERIAL SAFETY DATA SHEETS FOR ADDITIONAL INFORMATION:

(1) Add 10 mL of 12% copper ion concentrate solution to 990 mL of Stock Fuel.
(2) Add 100 mL of the solution from Step 1 to 1040 mL of Stock Fuel.
(3) Dilute 10 mL of the solution from Step 2 with 990 mL of Stock Fuel.

c. Peroxide Stock Solution—Dilute 335 mL of 90% by weight t-butyl hydroperoxide with 665 mL of n-Heptane.
d. Test Solution—Dilute 60 mL of Peroxide Stock Solution with 10 mL of Copper Ion Stock Solution and 930 mL of Stock Fuel.

5.7.2 Test Procedure:

a. A new injector must be used for each test fluid.
b. Precondition per 3.9.3.
c. Submerge the injector in the solution for 30 days at room temperature with the inlet port orientated in a manner to keep the injector full.

5.7.3 Assessment of Results—Each injector tested shall be evaluated under standard test conditions (per Section 3) and performance measured per 5.5.4 prior to and after completion of the tests.

5.8 Physical Tests—Fuel injectors are subjected to various mechanical loads. These loads occur during manufacturing, testing, handling, and installation in the vehicle fuel system. During actual vehicle service, the injector is also subjected to various shock and vibrational loads. The purpose of physical testing is to ensure that the injector's flow performance, electrical characteristics, and absence of leakage will remain within specification after being subjected to these types of forces.

5.8.1 Test Fixture Mounting—Axial load, bending moment, and torsional loads are applied to the injector during installation and removal to overcome the resistance of O-rings or other elastomeric members used for the purpose of sealing, thermal and mechanical isolation, and compensation for part variations. They are also subjected to loads resulting from mounting the fuel rail and/or retaining the injector.

On most designs, the upper half of the injector contains the electrical connector and the lower half the fuel metering section. The loads are usually applied to the injector by pushing and twisting the upper half relative to the lower half. One fixture design will not accommodate all injectors because of the variety of injector designs and mounting methods in use. The fixture must take into account the specific injector design and application. The loads and fixtures used may, therefore, necessarily deviate from that recommended in the following sections.

5.8.2 Assessment of Performance— Reference 5.5.4.

5.8.3 Axial Test Procedure—The injector shall be mounted to a suitable fixture per the application requirement (Fig. 20) and subjected

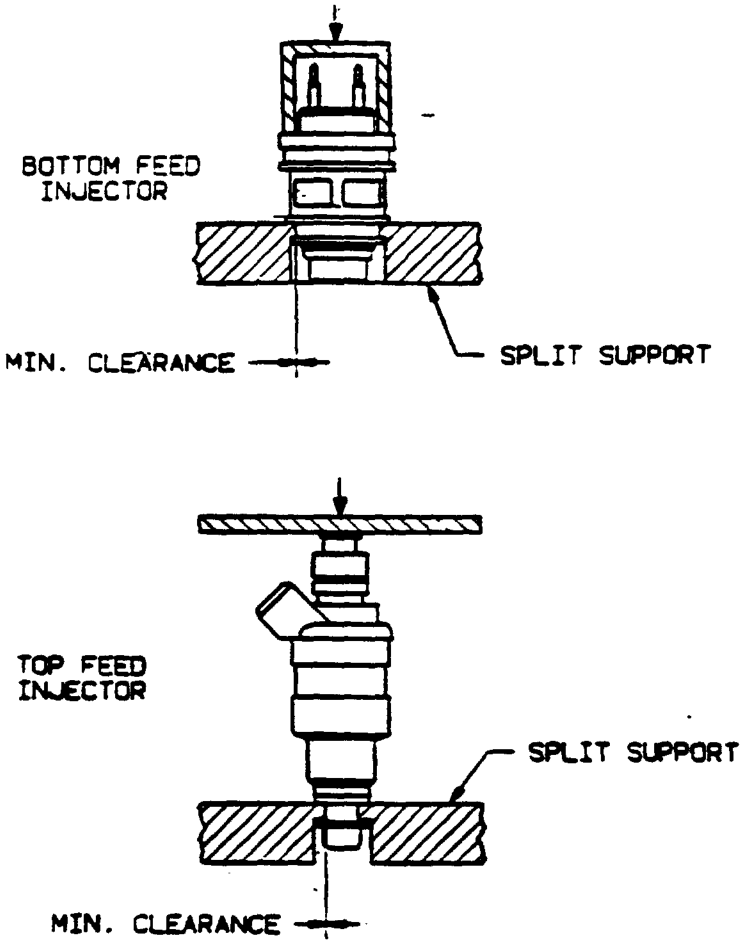


FIG. 20—AXIAL LOAD FIXTURE

to a force (typically 600 N) applied along the longitudinal axis of the injector.

5.8.4 Torsional Moment Test Procedure —The injector shall be mounted in a suitable fixture with the body fixed (Fig. 21) and a torsional moment (typically 0.6 Nm) applied to both ends for 5 s about the longitudinal axis of the injector.

5.8.5 Bending Moment—The injector shall be mounted in a suitable fixture (Fig. 22) and subjected to a bending moment (typically 6.0 Nm) for [illegible] s.

5.8.6 Vibration Test Procedure—Cap the injector inlet and outlet with the injector full of test fluid. Mount the injector in a vibration test fixture (Fig. 23) that duplicates the application mounting. Vibrate the injector in each of the three axes (longitudinal, lateral, and vertical). The vibration schedule is to be random with the frequency controlled over the range of 5 to 2000 Hz, based on the actual vehicle application. Test duration is to be per the customer requirements and may be accelerated per random vibration practices (Reference Military Standard 810-D). Accelerometers should be placed at the same location as per vehicle data acquisition. Vehicle data collection should encompass any conditions that may represent worst customer usage.

5.8.7 Shock Test Procedure—Cap the injector inlet and outlet with the injector full of test fluid. Mount the fuel injector onto a shock test fixture that duplicates the application mounting (Fig. 23). Perform impacts at 30 G's input load for a duration of 11 to 14 ms, six times with the injector in the vertical position (valve tip pointing downward) and six times with the injector in the horizontal position.

5.9 Bench Durability—This procedure defines a uniform test for evaluating the minimum acceptable durability level of a given gasoline fuel injector design.

5.9.1 Flushing Procedure—All test samples are to be cycled with test fluid for 1 min at a PW of 2.5 ms and a period of 5.0 ms.

5.9.2 Injector Test Conditions:

a. Fuel Temperature Test Range—17 to 30°C
b. Fluid—Indolene
c. Fluid Condition—A fresh supply of fluid is to be used at the start of every test, and changed at every 100 x 10^6 cycles of test (approximately 139 h)
d. Pressure—Determined by application
e. PW—2.5 ms
f. Period—(repetition rate)—5.0 ms
g. Duration: Subject to application
   Typical PFI 600 x 10^6 pulses
   Typical CFI 900 x 10^6 pulses

5.9.3 Performance Criteria—The test samples shall be evaluated for the following flow criteria:

a. Percent Static Flow Shift

$$\frac{\text{End of Test Flow} - \text{Start of Test Flow}}{\text{Start of Test Flow}} \times 100 = \%\ \text{Static Flow Shift}$$

b. Percent Q_d Shift at 2.5 ms PW and 10 ms Period (calculated same as above)
c. Leakage Specification—All test samples must be evaluated for leakage as specified in 4.1.21.1.

5.9.4 Frequency of Performance Checks —The test samples shall be evaluated for the above criteria at least prior to the start and on completion of the test schedule.

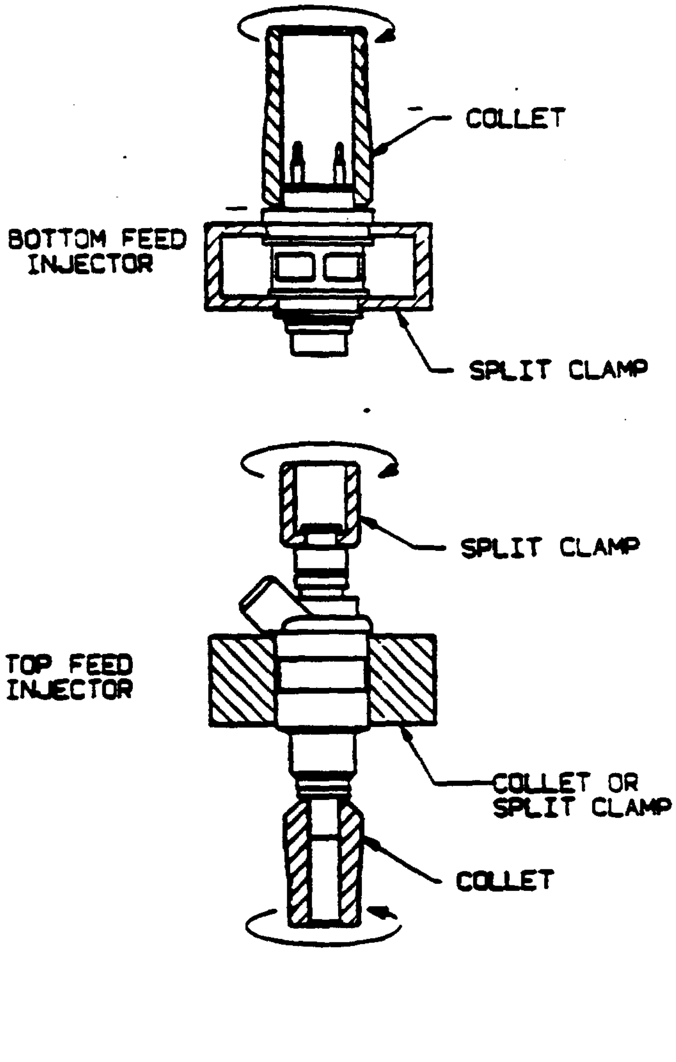


FIG. 21—TORSIONAL LOAD FIXTURE

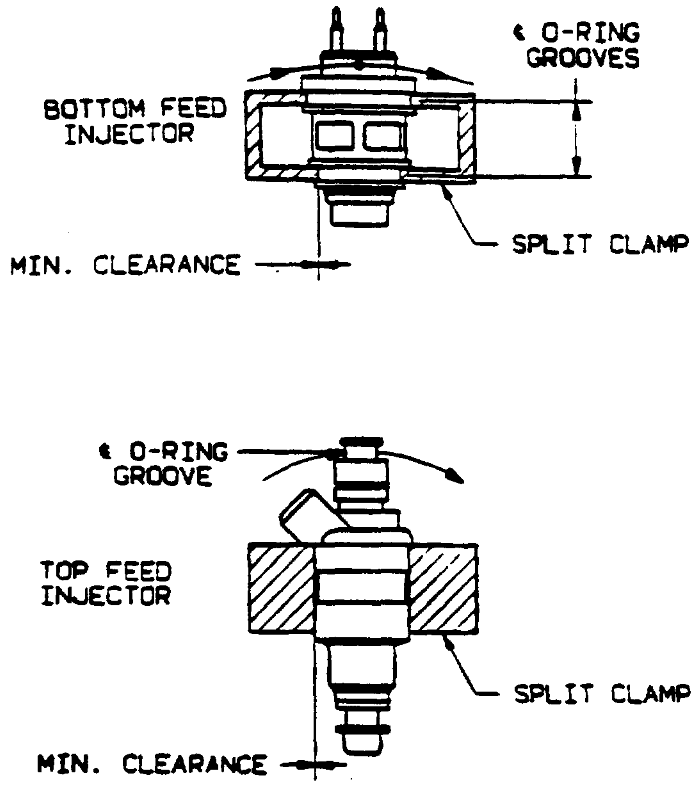


FIG. 22—BENDING MOMENT FIXTURE

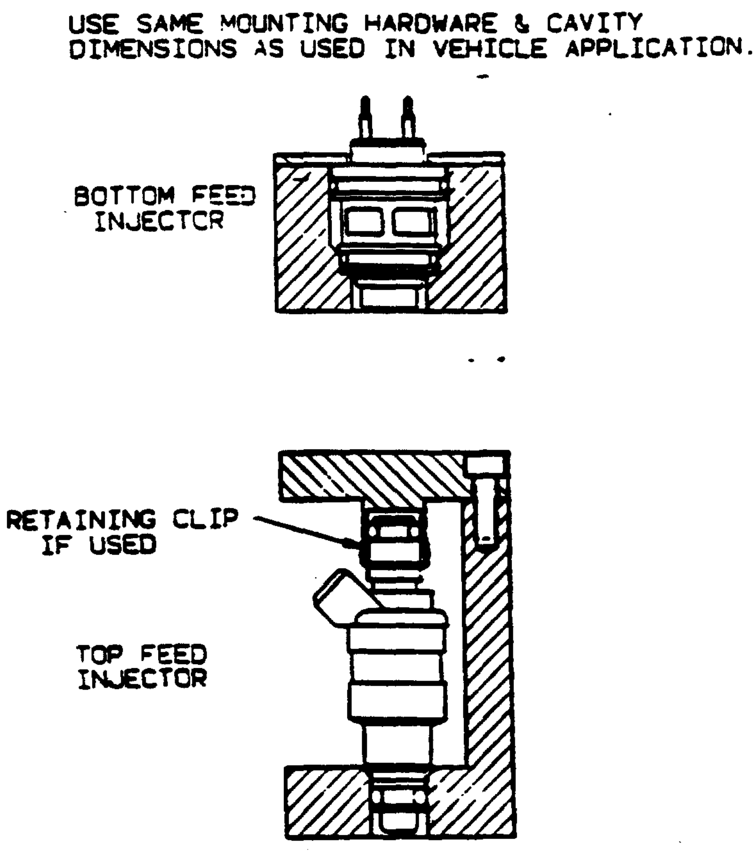


FIG. 23—SHOCK AND VIBRATION FIXTURE

New Designs/First Piece Samples will require additional flow test points during the accumulation of test cycles. See the recommended flow schedule for such cases as follows:

0 Cycles
25×10^6 Cycles
50×10^6 Cycles
100×10^6 Cycles
Continue at 100×10^6 Cycle intervals until end of test

5.10 Hot Lean Shift—Fuel injectors exhibit varying degrees of "hot lean shift" when operated at high temperatures. An extreme condition will usually occur in hot weather after a running engine has been shut down for about 30 min and then restarted. Both the injector and fuel temperature will rise during the "soak" period, causing reduced flow rates after the restart. The injector flow rates will gradually recover to normal levels as temperatures drop to a stable operating range. The magnitude of the lean shift is related to the injector design, fuel system components, injector's environment and the fuel characteristics. The degree of lean shift and its effect on driveability are best evaluated in a running vehicle. Fig. 24 illustrates the observed hot lean shift and the gradual recovery to stable conditions for three injector designs.

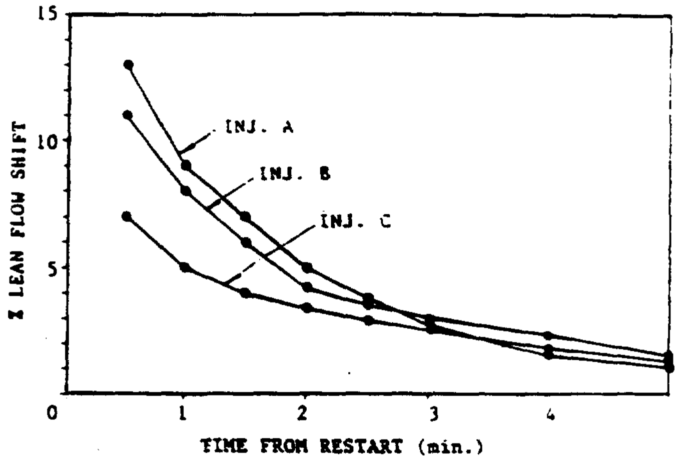


FIG. 24—HOT LEAN SHIFT

6. Test Equipment

The purpose of this section is to provide basic information on test equipment used in measuring fuel injector performance characteristics according to the specifications described in Sections 4 and 5. Recommendations are given for the design of the test flow head and hydraulic circuit for the bottom and top feed injectors, instrumentation resolution, and driver board connections.

The test equipment must be capable of precisely testing various electronic injector designs, preferably in mass flow units. The equipment and installations must be in compliance with all applicable fire and safety codes and regulations.

6.1 Hydraulic System—To assure that the test stand is versatile enough to evaluate the various injector design characteristics, the hydraulic system should be capable of operating with n-Heptane, Indolene, and mineral spirits as specified in 3.1. The recommended hydraulic system plumbing diagram is shown for a bottom feed injector in Fig. 25 and for a top feed injector in Fig. 26.

The test fluid pump must be capable of delivering 20 g/s of test fluid at a stable pressure of 700 kPa to the inlet of each injector. The test fluid filtering system must be 5 μm absolute or better. The test stand must be equipped with a heat exchanger to assure that the test fluid temperature is maintained constant within ±1°C throughout the test. To assure that the required accuracy to measure injector performance is met, the test fluid pressure regulation system must be capable of controlling the inlet test fluid pressure to the injector inlet with an accuracy of ±0.10 kPa in the range of 40 to 500 kPa. To eliminate any effect of the fluid head on injector inlet pressure, the pressure measuring device should be mounted in the same horizontal plane as the injector inlet. To minimize the effect of fluid pressure pulsations caused by the pump, the test stand hydraulic system must include an air dampened flow head. The trapped air test head for use with bottom feed injectors is shown in Fig. 27 and that for the top feed injectors in Fig. 28. The trapped air pocket must be precharged to maintain a minimum air volume of 30 cc at fuel system pressure.

Table 4 summarizes the test equipment resolution required to achieve the desired accuracy of the reported data and control variables.

6.2 Electrical—The wiring diagram for the injector, injector driver, and power supply is shown in Fig. 29. Because of the different injector drivers used in the automotive industry, it is recommended that the test stand be equipped with an interchangeable (plug-in) type driver board, 4-1/2 x 6-1/2 in with the numerics on the component side (see Fig. 30).

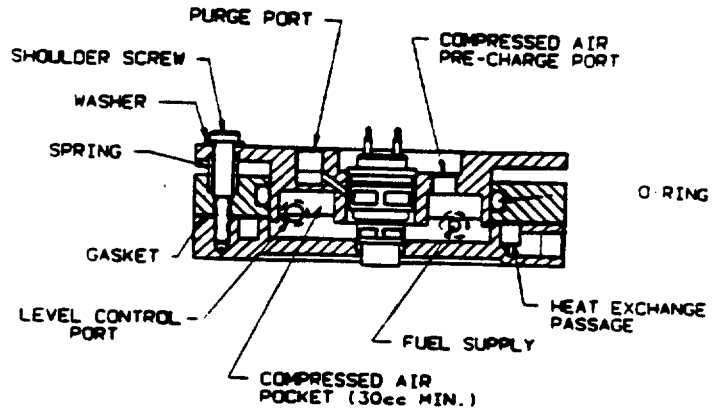


FIG. 27—BOTTOM FEED INJECTOR TEST HEAD

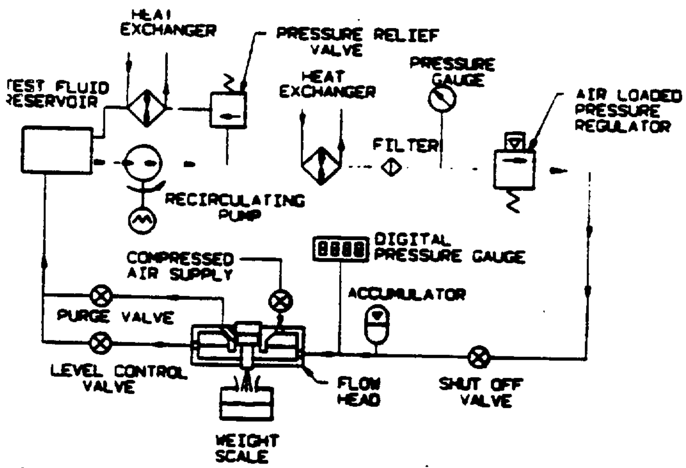


FIG. 25—HYDRAULIC SCHEMATIC FOR BOTTOM FEED INJECTOR

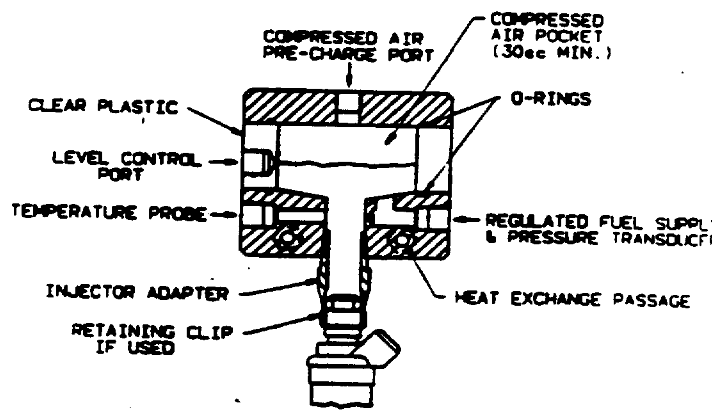


FIG. 28—TOP FEED INJECTOR TEST HEAD

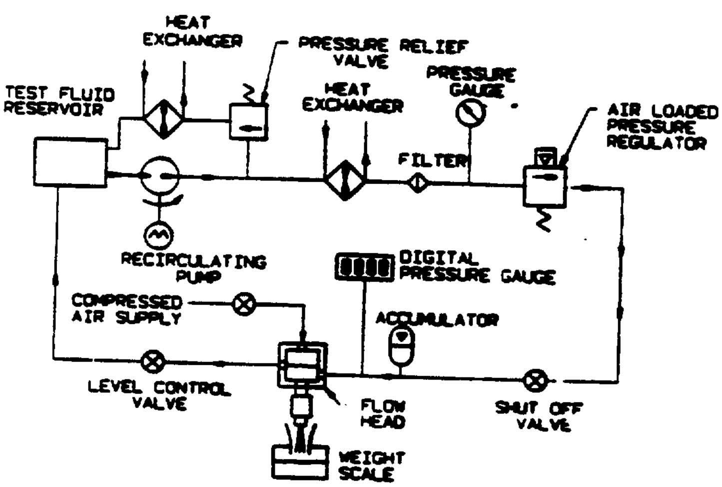


FIG. 26—HYDRAULIC SCHEMATIC FOR TOP FEED INJECTOR

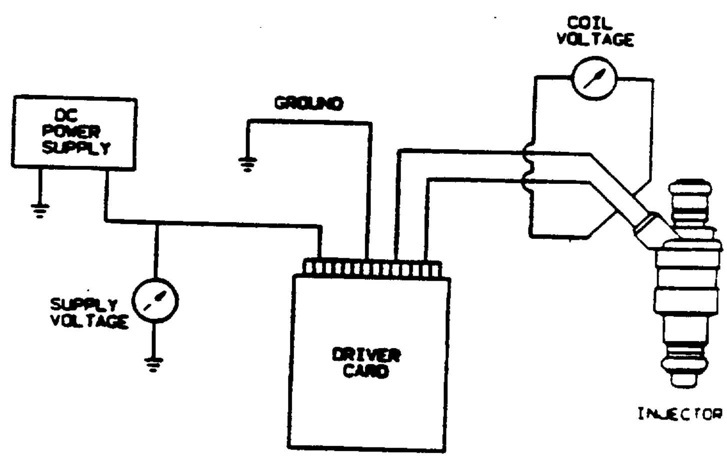


FIG. 29—ELECTRICAL WIRING DIAGRAM FOR FUEL INJECTOR TESTING

TABLE 4—ELECTRONIC FUEL INJECTOR TEST EQUIPMENT MEASUREMENT ACCURACY

CHARACTERISTIC	REPORTED RESOLUTION	EQUIPMENT RESOLUTION	CONTROL
Voltage Across Injector Terminal (volts)	XX.XX	±0.005	±0.01
Test Fluid:			
• Pressure (kPa)	XXX.X	±0.05	±0.10
• Temperature (°C)	XX.X	±0.05	±1.0
• Specific Gravity	X.XXX	±0.0005	
• Kinematic Viscosity (cSt)	X.XXX	±0.0005	
Static Pull-In Current (amps)	X.XX	±0.001	
Static Drop-Out Current (amps)	X.XX	±0.001	
Injector Coil Resistance (ohms)	XX.XX	±0.005	
Inductance (mH)	X.XX	±0.005	
Opening Time (ms)	X.XX	±0.005	
Closing Time (ms)	X.XX	±0.005	
Ambient Room Temperature (°C)	XX.X	±0.05	±3.0
Min Opening Voltage (volts)	X.XX	±0.005	
Pulse Width (ms) (Range = 0.01 to 99.99 ms)	XX.XX	±0.005	±0.001
Period (ms) (Range = 5.0 to 99.99 ms)	XX.XX	±0.005	±0.001
Weight of the Test Fluid (g)	X.XX	±0.005	
Dynamic Flow (mg/pulse)	XX.XX	Calculated	
Static Flow Rate (g/s)	XX.XXX	Calculated	

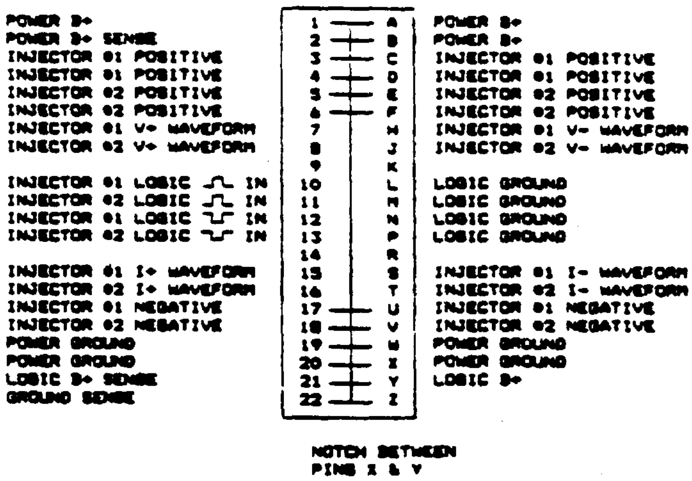


FIG. 30—INJECTOR DRIVER EDGE CONNECTIONS

FUEL INJECTION SYSTEM FUEL PRESSURE REGULATOR AND PRESSURE DAMPER—SAE J1862 FEB90

SAE Recommended Practice

Report of the Gasoline Fuel Injection Standards Committee approved February 1990.

Foreword—A fuel pressure regulator in an electronic fuel injection system is located downstream of the injectors and maintains a controlled differential pressure across the injectors for all engine operating conditions. Fuel delivered to the engine is metered by the length of time the injector is open and the controlled differential pressure. Typical fuel injection systems are shown in Figures 1 and 2.

The most commonly used pressure regulator is a hydromechanical bypass pressure relief device that is capable of sealing the fuel from returning to the fuel tank when closed. Typical fuel pressure regulators are shown in Figures 3 and 4. The regulator consists of two chambers separated by a diaphragm. The fuel chamber contains a fuel inlet, a fuel outlet, and a valve. The air chamber contains a spring and is usually referenced to the pressure condition of the discharge side of the injector(s). When the fuel pressure exceeds the set point pressure, the diaphragm raises the valve off the seat of the outlet passage and the excess pressure is relieved by permitting fuel to flow back to the fuel tank. The actual fuel system pressure can deviate from the desired value due to an accumulation of the following effects: slope, repeatability, hysteresis, response accuracy to a reference pressure signal, and production variability from regulator to regulator. Figure 5 illustrates the relationship of the fuel pressure to the manifold pressure.

Several other types of regulators have been developed but are generally used to correct a system problem such as the need for dual system pressure or the need to extend the dynamic range of the fuel system.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1995	Final Phase 2 Report: September 1994–September 1995

4. TITLE AND SUBTITLE

Development of a Dedicated Ethanol Ultra-Low Emission Vehicle (ULEV)—Phase 2 Report

5. FUNDING NUMBERS

(C) YAW -3-12243-01
(TA) FU521010

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Southwest Research Institute
P.O. Drawer 28510
San Antonio, TX 78228-0510

8. PERFORMING ORGANIZATION REPORT NUMBER

DE95013145

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NREL/TP-425-8195

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

UC-1500

13. ABSTRACT *(Maximum 200 words)*

The objective of this 3.5-year project was to develop a commercially competitive vehicle powered by ethanol that can meet California's ULEV standards and equivalent corporate average fuel economy energy efficiency for a light-duty passenger car application. This report summarizes the second phase of this project, which lasted 12 months. It documents two baseline vehicles, the engine modifications to the original equipment manufacturer engines, advanced aftertreatment testing, and various fuel tests to evaluate the flammability, lubricity, and material compatibility of the ethanol fuel blends.

14. SUBJECT TERMS

Alternative fuel vehicle, ultra-low emissions, engine modifications, equivalent corporate average fuel economy, light-duty passenger car

15. NUMBER OF PAGES

82

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT